STEAM REMEDIATION OF CONTAMINATED SOIL:

A SIMULATION STUDY

by

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DEDICATION

I dedicate this report to my loving, caring, and devoted wife, Cathy, and to my supportive and forgiving children, Glenn, Allen, and Karen. Without their support and devotion, this report would have been impossible.

ACKNOWLEDGMENTS

I gratefully acknowledge the United States Navy Civil Engineer Corps for providing me the opportunity to pursue this advanced degree. I also would like to thank the University of Texas at Austin for its support, specifically the Department of Petroleum and Geophysical Science, and my immediate supervisors Drs. Mark A. Miller and Kamy Sepehrnoori. Special thanks must go to Computer Modeling Group for granting the use of their simulator. Finally, I extend my thanks to my fellow graduate students who assisted me in this endeavor by providing me with technical computing support.

ABSTRACT

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Several million underground and aboveground storage sites in the United States contain petroleum, solvents, and other hazardous chemicals. Of these storage sites, an estimated 30% are leaking their contents into the soil. While various technologies exist for the remediation of the contaminated soil, they are relatively incapable of fully cleaning the soil when the contaminant has a low water solubility or a low vapor pressure.

Under these conditions, steam stripping the contaminant from the soil can be of great use. Although the petroleum industry has used this process for many years, it is just now beginning to gain recognition in the remediation industry as a valuable tool. Several proprietary models have been developed for use in the unsaturated vadose zone, with some authors claiming that oilfield simulators cannot be used in this zone.

A commercial thermal compositional simulator was used to show that such simulators can indeed be used in this area. The program was compared against laboratory results for steam displacement of xylene as well as against a field test. In both cases, the simulator gave results comparable to those published by the respective authors.

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1. INTRODUCTION

Ease of transportation, storage, and issue has made the use of petroleum products a way of life for much of the world. However, with that ease also come the dangers of the very product upon which we have come to depend, sometimes for our very existence. Inherent with the use of petroleum-based compounds is the danger of inadvertent exposure. Such exposure can be in the form of vapors breathed into the body, physical contact with the skin, or ingestion either directly or by solution in drinking water. Of the more than two million underground storage tanks in use nationwide, the U.S. Environmental Protection Agency (EPA) estimates about 25 percent may be leaking (EPA, 1988). In addition to these, we must also concern ourselves with the many miles of production and transportation pipelines, both buried and above ground, that may have a tendency to leak.

In the case of some contaminants, the historical use of pump and treat methods for cleanup is practicable. These contaminants are reasonably soluble in water. However, in the case of many petroleum fuels and solvents, this method does not yield good results, and requires a great deal of time. When light petroleum products are the contaminant, soil vapor extraction (SVE) is an accepted and practical method of recovery. Unfortunately, the vapor pressures of liquids such as diesel fuel, gasoline, jet fuel, and commercial solvents are such that at the normal pressures and temperatures found in the soil, the contaminants are not readily recovered by SVE.

The application of steam to oilfield reservoirs is a much-studied, well-understood process. However, in the area of remediation, it is still considered an emerging technology by the EPA. The primary benefit of injecting steam into the contaminated zone is the elevation of the vapor pressures of the contaminants, leading to improved recovery rates. As the contaminants are heated they are vaporized and mobilized in the gaseous phase. In typical cases, the saturation levels of liquids and gases are such that the relative permeability of the gas is much greater than that of the water, leading to preferential gas production. With initial saturations of contaminants low, and further reduced by production of vaporized components, the relative permeability to liquid contaminant becomes quite low indeed.

In this process, steam is injected into the contaminated soil. The steam moves through the soil, contacting and vaporizing the contaminant, and is produced along with the mobilized contaminant. At the surface, the gases and liquids produced must be processed to recover the contaminant and monitor the amount of contaminant recovered.

2. LITERATURE REVIEW

Soil venting extraction (SVE) is a generally accepted method of recovering volatile contaminants from undersaturated soils. However, when the contaminant is not so volatile, as in the case of kerosene, diesel fuel oil, and JP-4 jet fuel, the normal SVE approach does not yield adequate results. This is because the vapor pressure of the contaminant is too low for this method to be of use.

The vapor pressure of these contaminants is directly related to the temperature of the material. Therefore, the injection of steam to raise the contaminant temperature, and therefore the vapor pressure, is a method worthy of consideration. While the injection of steam has been widely used for heavy and light oils in the petroleum industry, the EPA still considers it to be a developing technology for the purpose of contamination remediation.

2.1 MODELING OF STEAM REMEDIATION

While a multitude of numerical models has been developed for the SVE process, only a few have been developed for steam remediation of contaminated soils: Falta et al. (1990), Adenekan and Patzek (1993), Lord (1987), and Wilson and Clarke (1992).

Lord's model assumes soil gas pressures near the steam injection well can be derived by solving Laplace's equation in terms of pressure. As

Wilson and Clarke comment, this condition is applicable to incompressible fluids. For steam pressures approximately equal to 1 atm, this assumption introduces little error. However, if higher steam pressures are used, e.g., 30-50 psi, Wilson and Clarke assert much larger errors could occur. In most cases in the shallow unsaturated zone, injection pressures will be kept low to avoid fracturing. Thus, it seems Lord's approach may be valid.

Further, Lord's model utilizes the method of images to obtain a solution. However, Wilson points out this yields an image potential that does not satisfy the no-flow boundary condition of the bottom of the unsaturated zone. A final criticism of Lord's work by Wilson and Clarke is that the steam flows are assumed to be purely diffusive. They contend that under the flow rates likely to be encountered, diffusion is most probably unimportant except on a rather microscopic level.

Wilson and Clarke's model is based on gases that obey the ideal gas law, and derives a solution from Laplace's equation in terms of pressure squared. This model assumes isotropic and constant permeability, and that the adsorption isotherm of the contaminant is linear. Wilson and Clarke also use the method of images, but derive a solution that goes to zero at the ground surface, and which satisfies a no-flow boundary at the water surface. The model was used to investigate the performance of a single steam injection well system, but the authors consider the model to be neither definitive nor final, and leaves a number of factors to be addressed. It does not address changing conditions during steam injection startup, nor does it allow for anisotropy.

Adenekan and Patzek's model is a compositional simulator that models the flow of mixtures of Nonaqueous Phase Liquids (NAPLs) through the unsaturated zone and into the aquifer. This model allows for arbitrary densities, boiling points, and viscosities, and is three-dimensional, fully implicit, three-phase, thermal-capable, and multicomponent. Adenekan and Patzek contend that existing commercial thermal compositional simulators cannot be used to study NAPL contamination because of transport and recovery mechanism differences. They go on to say that while their model is capable of complete elimination of a particular phase in any particular grid block, most oil reservoir simulators are written with heavier oils in mind and lack that capability. They also cite the lack of flexibility of interaction at the ground surface between the subsurface contaminants and the atmosphere, as well as the lack of importance of diffusion in oil reservoir codes.

Adenekan and Patzek's model was validated using laboratory data from a one-dimensional, benzene-toluene water and steam flood data set. They also used data from a steam injection pilot near the Lawrence Livermore National Laboratory for history matching. Their results show that the dominant recovery mechanism is vaporization, and that cleanup times are most sensitive to the permeability of the porous medium.

Falta (1990) developed a model for displacing NAPLs in shallow subsurface systems. This model is three-dimensional, three-phase capable, and incorporates heat transfer and equilibrium mass transfers of the organic

component among all three phases. Falta validated his model by comparison with laboratory experiments.

2.2 FIELD TESTS

In the area of SVE, numerous field tests and applications have been performed. However, in the case of steam extraction, the first field application in the U.S. did not come about until 1988. Stewart and Udell (1989) oversaw a project at the Solvent Service site in San Jose, California. In this case, a contaminated zone 12 ft in diameter and 18 ft deep was surrounded by six steam injection wells. The surface was sealed with cement and epoxy to prevent surface escape of toxic vapors, and a central production well was equipped with a vacuum and condenser system. Over the course of the pilot study, approximately 30 days, contamination levels were reduced to 10 ppm as opposed to up to 30,000 ppm initially. About 770 lbm of pollutants were removed.

More recently, at the Lawrence Livermore National Laboratory in Livermore, California, steam was injected into a "Clean Site" as part of a pilot for the Gasoline Spill Area (GSA) cleanup project (Udell, 1990). After 24 days of continuous injection, the steam zone had reached an extent of 8,000 m^3. Cross-hole electrical tomography provided excellent three-dimensional imaging. Full-scale clean-up of the GSA site was scheduled to begin in 1992.

AWD Technologies, Inc. (1992) performed a test of their steam stripping technology at the San Fernando Valley Superfund Site, California. Reported efficiencies were in the range of 99.92 to 99.99 percent for removal of volatile organic compounds. Effluent water produced was in compliance with regulatory requirements for TCE and PCE. AWD also has a unit operating at the Lockheed Aeronautical Systems Company in Burbank, California. This unit has been on-line for over three years, and has been operational 95 percent of the time.

Novaterra, Inc. (Toxic Treatments, 1991) demonstrated their operation at the Annex Terminal, San Pedro, California, in 1989. This method incorporates two augers operating simultaneously. One auger is used to penetrate and supply steam to the soil, while the other auger is used to penetrate the soil and capture the toxic vapors generated. Both augers are fitted with cutting bits 5 ft in diameter, and are capable of operating to a depth of 27 ft. A metal shroud is placed over the area being treated to prevent vapors from escaping to the atmosphere. An area of approximately 29 ft^2 in size can be treated at a time. This process reportedly can lead to substantial variations in residual levels of pollutants, and is not designed for semivolatile organic compounds. Other limiting factors are the maximum slope of the area (1%), minimum total area (2 acres), sufficient compaction to handle the weight of the unit, and removal of underground and overhead obstacles.

This treatment procedure can reduce the level of contaminants to lower than 100 ppm, and has an average efficiency rating of 85%.

Semivolatile compounds can be reduced by a factor of 50%. Soil gases continue to escape the block last treated, but such emissions decline quickly with time. Costs for this method range from $250/yd^3 to over $300/yd^3.

In 1984, a series of tests was run (Heijmans, 1989) in the Netherlands using a system of injection and production wells and a vacuum bell. In this study, a vacuum bell 2m x 2m was placed on the ground and steam injected through four lances to a depth of 4.5m. After steam stripping, all of the contaminants were determined to be below detectable levels. In 1985, several additional tests were conducted. Soil analysis showed that 97 percent of the contaminant had been removed, and that the maximum residual level was 220 mg/kg. After both series of tests, however, the authors still considered steam stripper performance to be poor.

3. PROBLEM STATEMENT

The problem undertaken for this report was to determine the applicability of a commercial, oilfield simulator to model steam remediation of contaminants in the unsaturated vadose zone. Computer Modeling Group's STARS simulator was used in this work. The simulator is thermal, fully compositional, and is capable of 2- and 3-D simulations involving up to six components. The approach to the problem was two-fold: (1) verify the applicability of the simulator against laboratory data and supporting simulation, and (2) compare simulation results with field data.

4. RESULTS

The overall strategy in this report was to first validate the simulator using laboratory data from Falta (1990). It was felt that this data would be the best documented data in terms of knowledge of physical parameters such as porosity, heat transfer coefficients, and relative permeability data. In addition, the results from this first set of runs would be compared against the results of Falta's model.

The second step would be validation of the simulator using field data. The pilot study of Stewart and Udell (1988) was used primarily due to its availability and its overall documentation of data. While an exact history match was neither the aim nor required, results which would be comparable were desired.

The STARS simulator is a three-phase multi-component thermal and steam additive reservoir simulator. It is capable of handling up to six simultaneous components and can be run in fully implicit and adaptive implicit modes. STARS allows naturally fractured reservoirs and dispersed components (including foam) to be used. The coordinate system can be either radial, variable thickness/variable depth, or cartesian, with local grid refinement available.

4.1 LABORATORY COMPARISON

The STARS simulator was run using data from Falta (1990) in which he validated his model using data from Basel and Udell (1989). Basel and Udell constructed a sandpack that was 5 cm thick, 91.5 cm long, and 30.5 cm tall. They filled the tank with a very coarse sand with an average permeability of 10 μm^2 and a porosity of 40 percent. The bottom third of the tank was saturated with water, the middle third was saturated by the capillary fringe, and the top third was saturated with residual water from a previous steam injection experiment. The sides of the tank were double-walled lexan. Xylene was injected at a point source at the top of the tank and then allowed to migrate downward to an equilibrium state. After the xylene had come to equilibrium it was displaced with steam. Fluid and sandpack simulation data are shown in Table 4.1. The sandpack grid scheme is shown in Fig. 4.1.

Falta investigated three scales of steamflood: laboratory, small field, and large field. The three simulations use the same mesh shape and steam mass injection rate. The physical dimensions of the simulations were scaled upwards by a volumetric factor of 1000 between each run. Thus, the small field scale grid blocks are 10 times larger in each dimension than the laboratory scale, and those for the large field scale are 10 times larger than the small field scale. The permeability was changed to keep the ratio of gravitational forces to viscous forces approximately equal for each scale. The total amount of xylene injected was increased by the same proportion.

The injection rate was kept constant, but the total injection time was increased. Likewise, the equilibrium time was similarly increased.

The STARS simulator was run at laboratory and small field scales for comparison against Falta's simulator results. Sandpack physical data, along with injection rates and fluid data were taken from Falta's work. Additional fluid thermodynamic data were obtained from Reid et al. (1987). In both the laboratory and small field scale cases, the saturation and temperature profiles (Figs. 4.2 through 4.18) were nearly the same as Falta's, as well as the time for complete recovery of the xylene.

In the small field scale case, the xylene is allowed to equilibrate until day 20 of the simulation. The initial lens which forms (Fig. 4.2) is similar to the lens which Falta shows. As the steam is first injected, it preferentially enters the upper layers due to a higher relative permeability. As the steam continues to be injected and the temperature of surrounding blocks increases, the resident water in the lower layers is vaporized and steam begins to enter them. The xylene lens starts to be affected by the incoming steam at around day 25 of the simulation (Fig. 4.7). The steam front at this point is quite vertical, with minor gravity override effects present (Fig. 4.8). As time progresses, the steam front remains vertically stable and the xylene is displaced toward the producer at the right side of the grid. Near the end of the displacement, the effects of gravity override become more pronounced (Figs. 4.13 through 4.18).

The time to recover the injected xylene is also very close to Falta's results. Falta required 0.019 days and 17.5 days of steam injection in the laboratory and small field scale, respectively. The simulator gave recovery times of 0.021 days and 22 days of steam injection. As was the case for Falta, the STARS simulator gave steam profiles that were nearly linear and provided good sweep. This indicates that steam injection would be a good candidate for remediation of xylene at the field level. Falta comments that pressures used in actual application would be much larger than those used in the simulation (113 kPa, 200 kPa for laboratory and small field scale, respectively). However, at shallow depths, the pressure would need to be kept low to avoid fracturing the contaminated zone.

Table 4.1: Sandpack Xylene Displaccment Simulation Data

Sandpack Data		
Block Thickness		
Laboratory Scale	0.1640 ft	Falta (1990)
Small Field Scale	1.640 ft	Falta (1990)
Block Height		
Laboratory Scale	.098335 ft	Falta (1990)
Small Field Scale	0.98335 ft	Falta (1990)
Block Length		
Laboratory Scale	0.19667 ft	Falta (1990)
Small Ficld Scale	1.9667 ft	Falta (1990)
Porosity	0.4	Falta (1990)
Permeability		
Laboratory Scale	100,000 md	Falta (1990)
Small Field Scale	1,000 md	Falta (1990)
Soil grain heat capacity	31 Btu/ft^3-F	Falta (1990)
Gas-Water capillary pressure constant	104.8 m^{-1}	Falta (1990)
Water mass injection ratc	27.9 lbm/day	Falta (1990)
Specific enthalpy of injected water	220 Btu/lbm	Falta (1990) (1989)
Injected xylene vol		Falta (1990)
Laboratory Scale	0.006277 bbl	Falta (1990)
Small Field Scale	6.277 bbl	Falta (1990)

Fluid Data, Xylene		
Molecular weight	106.2 gm/gm mole	Falta (1990)
Critical temperature, T_C	630.3 K	Falta (1990)
Critical pressure, P_c	37.3 bar	Falta (1990)
Boiling Temperature, T_b	417.6 K	Falta (1990)
Vapor pressure constants		
a	1.93577×10^5	Reid et al.
b	-6112.03	Reid et al.
c	-352.64	Reid et al.
Ideal gas heat capacity constants		
a	-3.571×10^{-2} Btu/lb-F	Reid et al.
b	7.4633×10^{-4} Btu/lb-F^2	Reid et al.
c	-2.3946×10^{-7}	Reid et al.
d	2.90848×10^{-11}	Reid et al.
Reference liquid density	880 gm/cm^3	Falta (1990)
Liquid viscosity constants		
a	0.157647 cp	Reid et al.
b	924.37 F	Reid et al.
vaporization enthalpy	182 Btu/lbm-F	Reid et al.

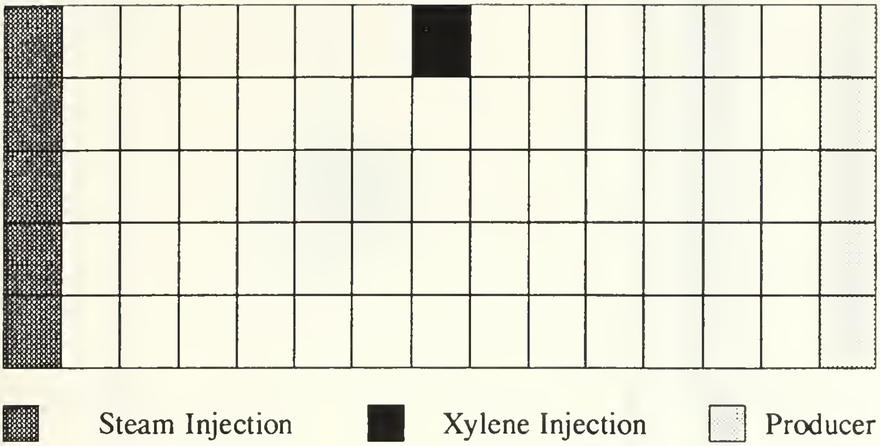

Figure 4.1: Sandpack grid scheme

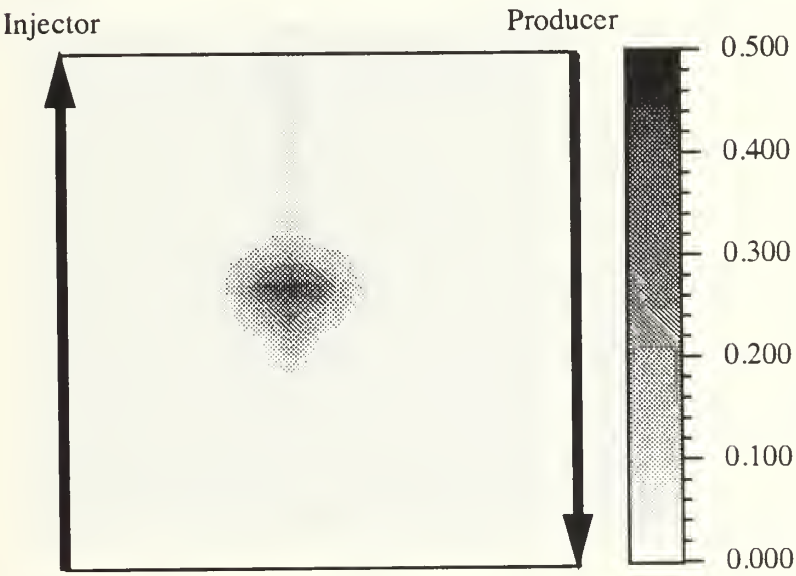

Figure 4.2: Sandpack xylene displacement, saturation profile, t= 17 days

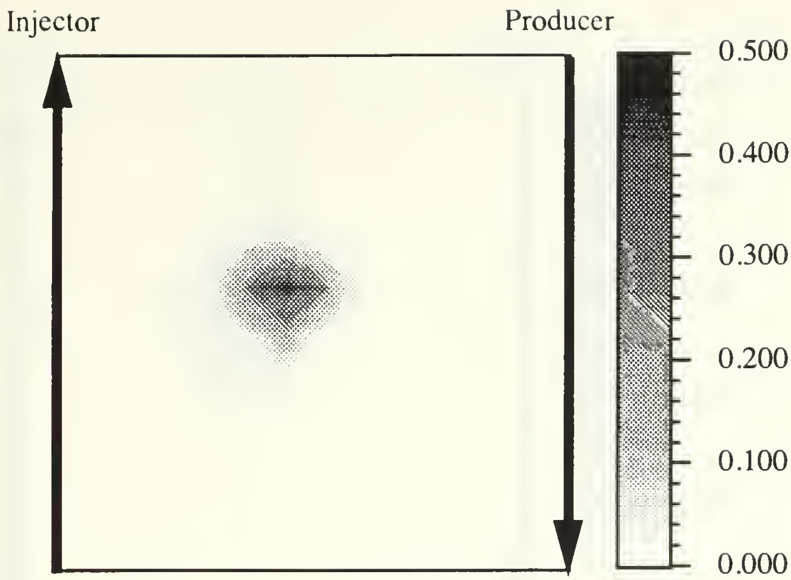

Figure 4.3: Sandpack xylene displacement, saturation profile, t= 20.5 days

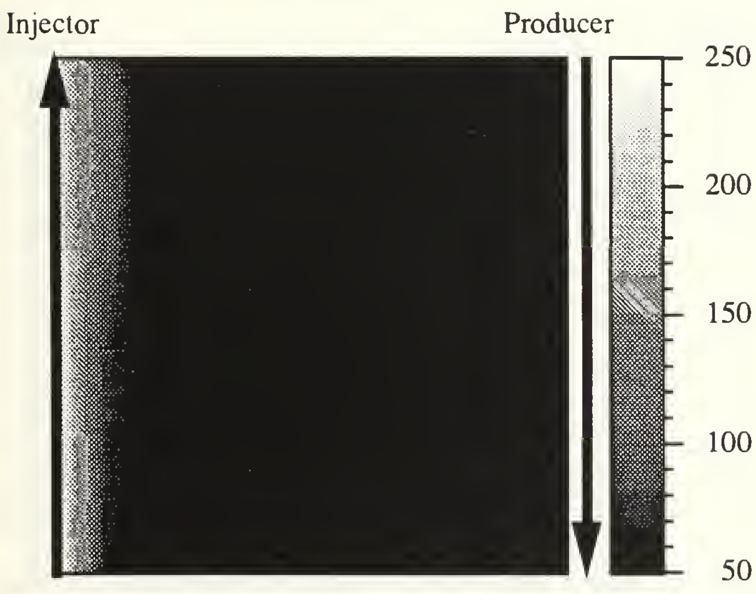

Figure 4.4: Sandpack xylene displacement, temperature profile, t= 20.5 days

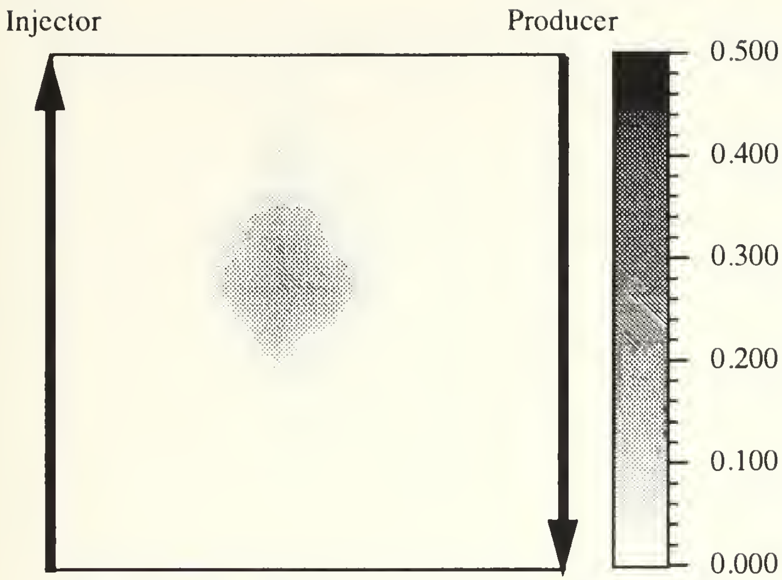

Figure 4.5: Sandpack xylene displacement, saturation profile, t= 23 days

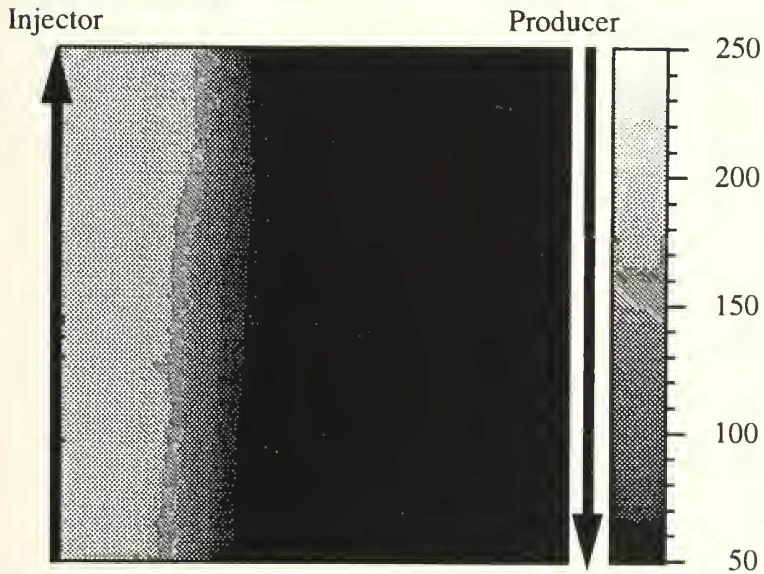

Figure 4.6: Sandpack xylene displacement, temperature profile, t= 23 days

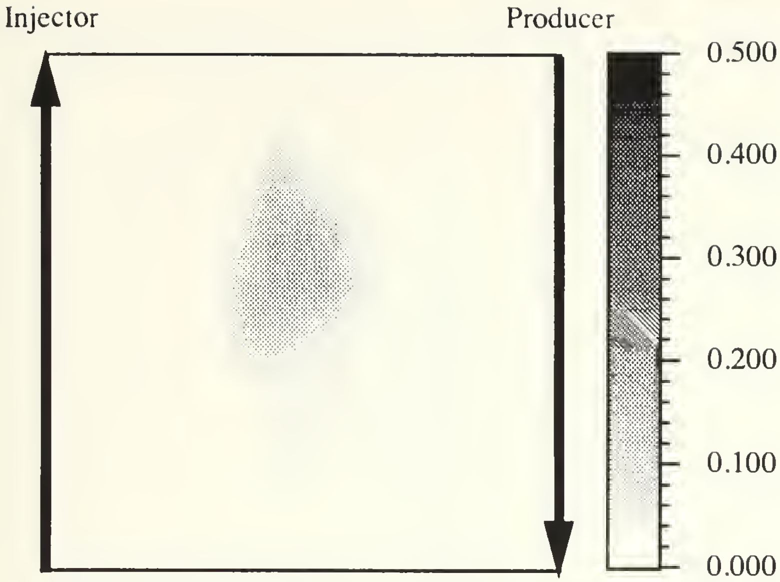

Figure 4.7: Sandpack xylene displacement, saturation profile, t= 25 days

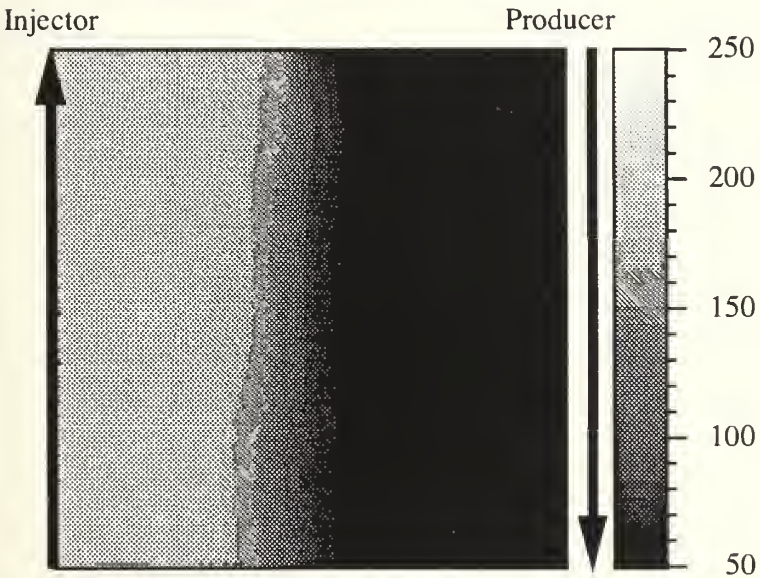

Figure 4.8: Sandpack xylene displacement, temperature profile, t= 25 days

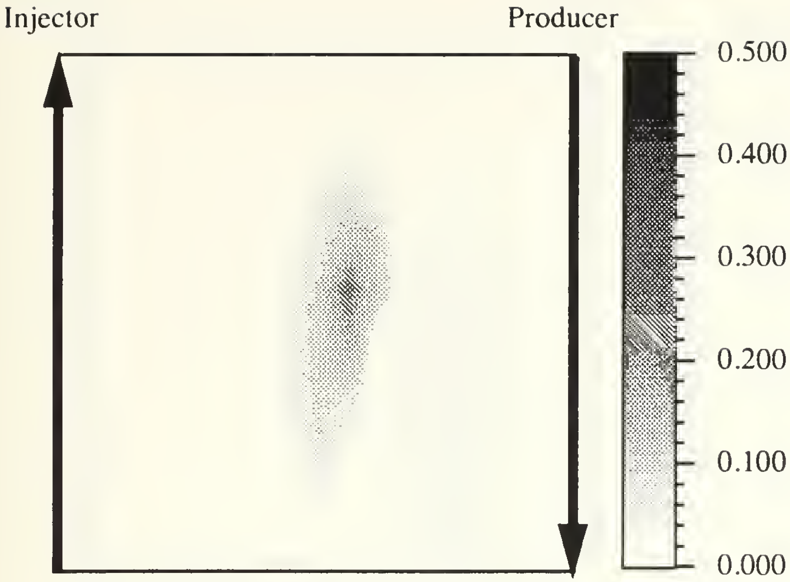

Figure 4.9: Sandpack xylene displacement, saturation profile, t= 28 days

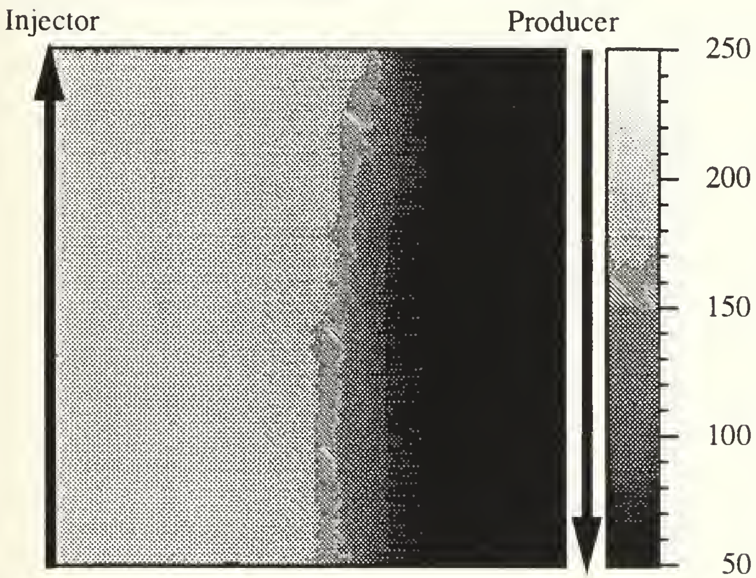

Figure 4.10: Sandpack xylene displacement, temperature profile, t= 28 days

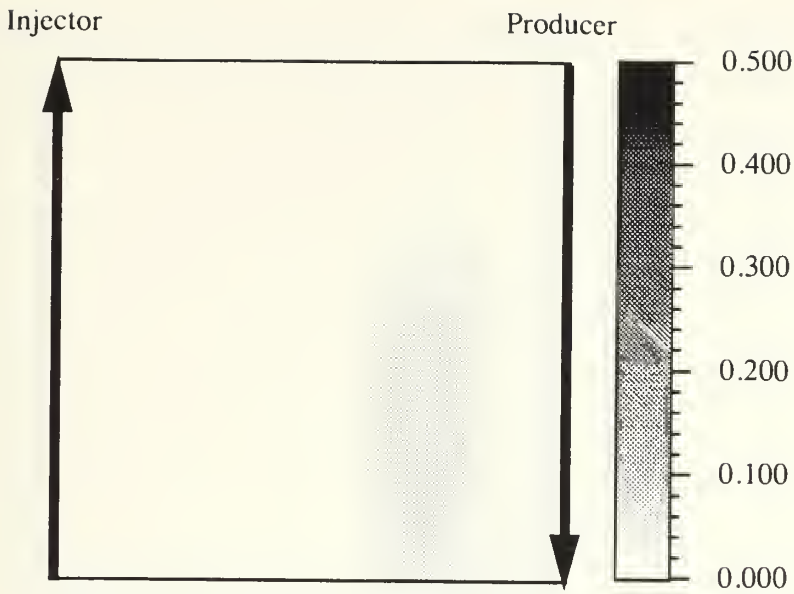

Figure 4.11: Sandpack xylene displacement, saturation profile, t= 32 days

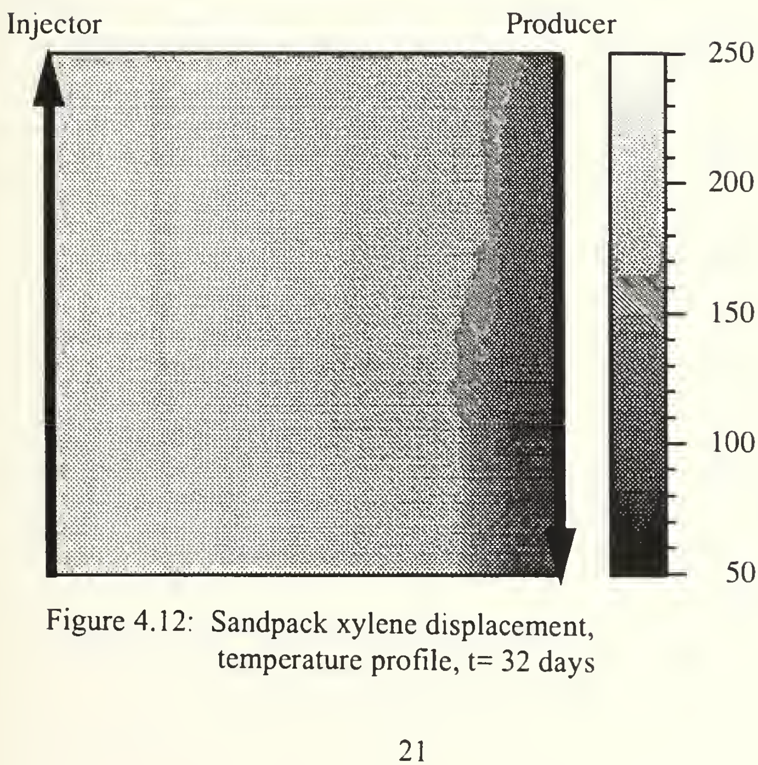

Figure 4.12: Sandpack xylene displacement, temperature profile, t= 32 days

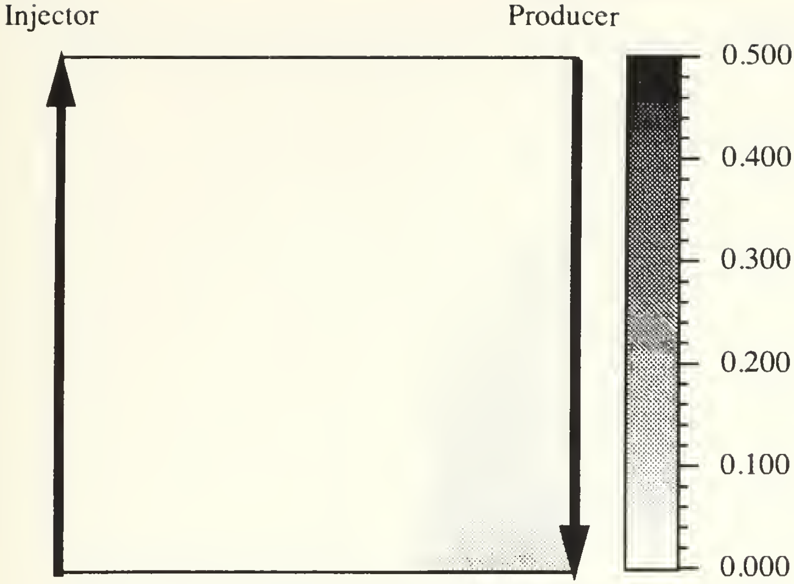

Figure 4.13: Sandpack xylene displacement, saturation profile, t= 35 days

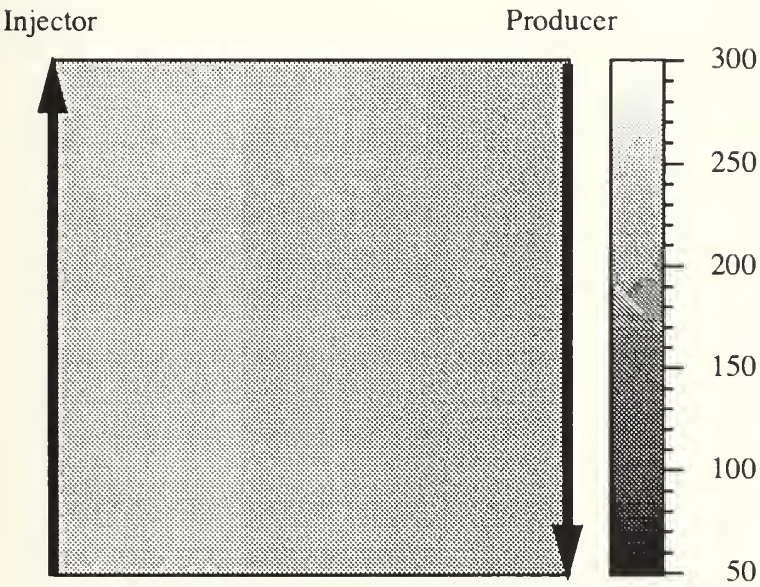

Figure 4.14: Sandpack xylene displacement, temperature profile, t= 35 days

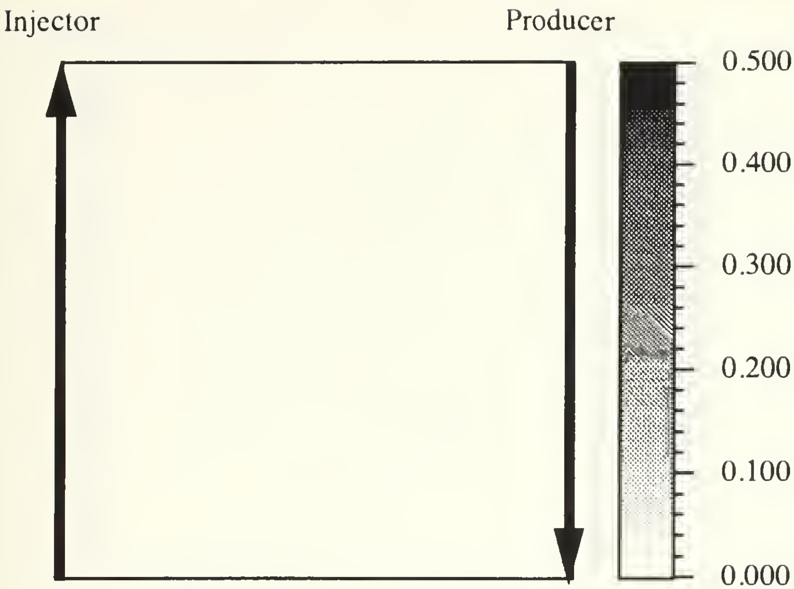

Figure 4.15: Sandpack xylene displacement, saturation profile, t= 40 days

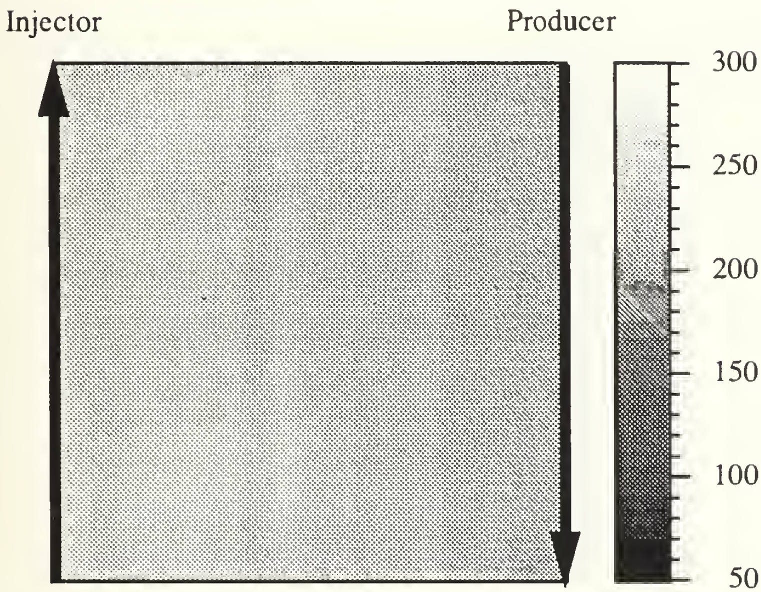

Figure 4.16: Sandpack xylene displacement, temperature profile, t= 40 days

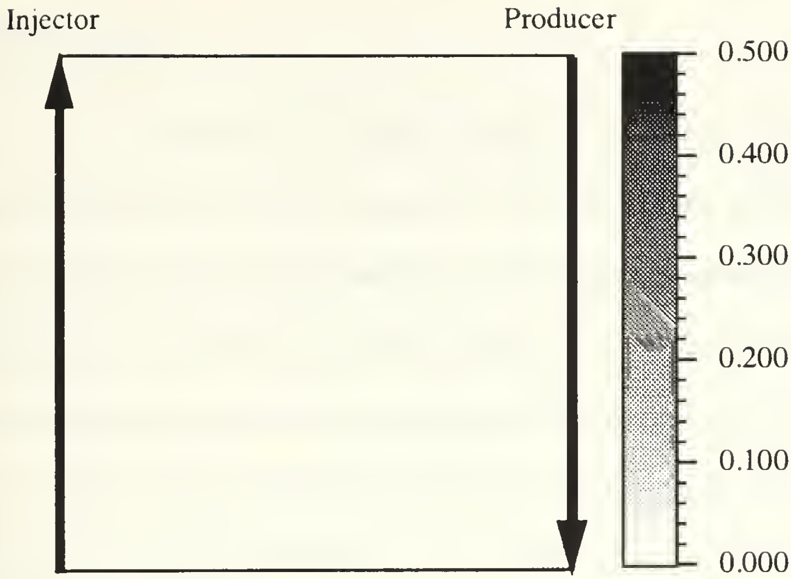

Figure 4.17: Sandpack xylene displacement, saturation profile, t= 42 days

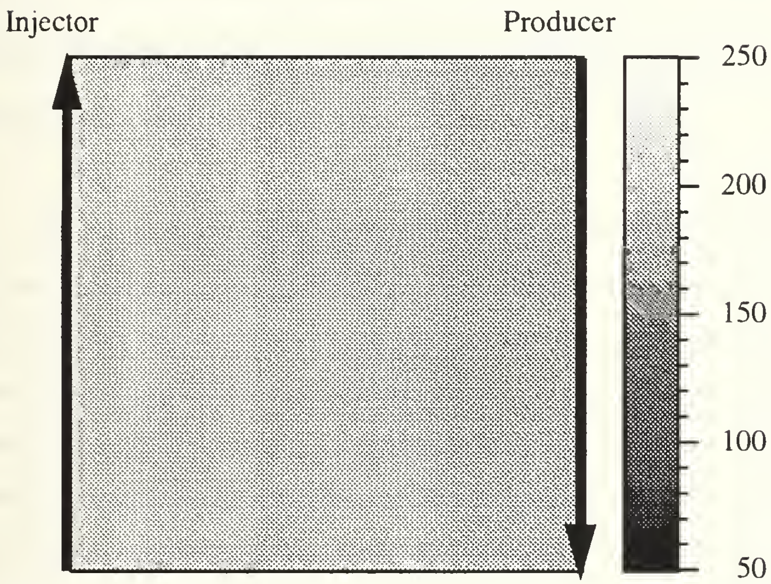

Figure 4.18: Sandpack xylene displacement, temperature profile, t= 42 days

4.2 FIELD TEST

Stewart and Udell (1989) reported on a pilot study of steam injection coupled with vacuum extraction at a site in California in 1988. The pilot study area was a small portion of a much larger contaminated zone within an area occupied by Solvent Systems, Inc. Various solvents from underground storage tanks and surface spills contaminated the soil, chiefly acetone, xylene, ethylbenzene, dichlorobenzene, thrichloroethane, trichloroethene, and tetrachloroethene. The chemicals contaminated the soil to a depth of 20 ft, with a concrete pad on top. The excavation and treatment of the soil was estimated to cost $9 million and would have disrupted ongoing use of the site. Therefore, in-situ methods were investigated for use.

As shown in Fig. 4.19, six injection wells and a central production well were installed for the pilot study. The injection wells were opened over the bottom one foot only, while the production well was opened over the entire thickness of the contaminated zone. Soil borings were taken to determine the initial level of contamination, and vacuums were drawn to determine formation permeabilities and heterogeneities. The field data as given by Stewart and Udell are shown in Table 4.2. The production well was placed on vacuum and jackpump. The injection wells were maintained at low pressure to avoid fracturing the soil. The wells were periodically

shut in and opened over a period of 30 days. After the conclusion of the pilot test, soil borings were taking to evaluate the recovery process. A summary of the injection and production schedule is shown in Table 4.3.

The STARS simulator was used in three separate runs for this situation. A complete 3-D study was made, as was a 2-D vertical cross sectional study. The cross-sectional study was further expanded to investigate the effects of various geometries of injection and recovery wells. As with the above comparison with Falta, all data that could be taken from Stewart and Udell was used. Other required fluid data was obtained from Reid et al.

The 2-D study was first run using a radial system with one vertical injection well and one vertical production well. A segment equal to one-sixth of the entire system was modeled, with the results being applicable to the complete area due to assumed homogeneity. The data used in this run are shown in Tables 4.2 and 4.3, and temperature and saturation profiles in Figs. 4.20 through 4.40. The swept zone starts out radial in shape, as seen in Fig. 4.20, but quickly becomes elongated as the effects of the production well are felt. However, the steam continues to sweep vertically as well (Fig. 4.24). The contaminant which is vaporized flows ahead of the steam and condenses, thereby forming a liquid contaminant bank. This can be seen in the figures by noting the darkened area adjacent to the swept zone. The swept zone enlarges somewhat linearly towards the top of the formation after steam breakthrough (Figs. 4.24 through 4.40).

The simulator was next run in a 2-D mode but with a horizontal injector located along the bottom of the zone and a horizontal producer along the top of the zone. This was run in cartesian coordinates. While the results from this run cannot be quantitatively extrapolated to the entire pilot study, it does show the qualitative difference in recovery times between vertical and horizontal injection and production geometries. The steam front proceeds linearly throughout the simulation, and the contaminant behaves as above for the vertical case. Simulator data are shown in Table 4.2 and the temperature and saturation profiles are shown in Figs. 4.41 to 4.47.

Finally, the simulator was used to model the full pilot in three dimensions. As above in the vertical mode, the wells were fully vertical, and the injection and production cycling data from the pilot study were used. The simulator data are shown in Table 4.2, and the temperature and saturation profiles are shown in Figs. 4.48 through 4.63. The overall behavior of the 3-D study was much the same as for the 2-D vertical study. The lower zones are swept first, followed by vertical migration of the steam. As the steam migrates, it vaporizes the contaminant in front of it. Due to the proximity of the injectors and producer, Stewart and Udell reduced the steam injection rate to avoid channeling steam to the producer. Additionally, the injection pressure was not equal in all injection wells. The effects of this can be seen in the temperature profiles by noting the lack of complete symmetry with respect to the production well.

As mentioned earlier, excavation and treatment would have incurred a tremendous cost. Pump and treat would have been impractical in this case due to the insoluble nature of the contaminants with respect to water. A pure vacuum recovery project would have recovered the contaminant, but probably to a lesser degree, and certainly over a much longer period of time. This conclusion is borne out by Stewart and Udell in their preliminary analysis of the pilot study itself.

The results from the runs in the two-dimensional cross-section showed complete remediation after approximately 61 days. The steam appears to break through after four days of steam injection, as compared to 32 hours in the actual field case. The primary method of recovery appears to be volatilization of the contaminant and recovery in the gaseous phase. This is what would be expected from a contaminant that is basically insoluble in water and is at saturation levels such that relative permeability is near or equal to zero.

In the case of the two-dimensional horizontal study, the injection and production wells were not cycled, but was kept on continuous operation. The resultant earlier steam breakthrough and recovery of the contaminant is also seen. After approximately 5.5 days the contaminant is completely recovered. This simulation shows the benefit of using the natural tendency of steam to rise through the formation. Additional simulation should be done to determine the optimum well spacing and location for a given remediation project.

The full 3-D study also shows good sweep of the contaminant in the area between the injectors and the producer. However, for reasons most likely related to incomplete knowledge of the physical parameters of the soil under study, a good history match with the published data is not made. The basic aim of this report, to show the applicability of the model to the unsaturated zone, is not tarnished by this. Whether it takes 30 days or 90 days to recover the contaminant, it is still a much more viable option than excavation and treatment, pump and treat, or pure vacuum extraction.

No discussion of simulation would be complete without mention of problems encountered while making a run. In this particular case, the use of steam causes its own unstabilities. One of the ways to handle steam injection was to maintain a small maximum time step size. Additionally, whenever injection or production wells were opened or shut in, the initial time step was reset to a very small value.

Other problems dealt with excessive amounts of data compiled by the simulator. It was necessary to make several runs of the same data but changing the output parameters to avoid generating too much data.

Table 4.2: Steam recovery pilot simulation data

Formation Data		
Block Height	2.0 ft	
Block Length	2.0 ft	
Block Thickness	2.0 ft	Stewart/Udell (1989)
Porosity	0.3	Stewart/Udell (1989)
Permeability	8700 md	
Soil grain heat capacity	31 Btu/ft^3-F	Stewart/Udell (1989)
Water mass injection rate	(See Table 4.3)	Stewart/Udell (1989)

Fluid Data, Xylene		
Molecular weight	106.2 gm/gm	Reid et al. (1987)
Critical temperature, T_C	630.3 K	Reid et al. (1987)
Critical pressure, P_c	37.3 bar	Reid et al. (1987)
Boiling Temperature, T_b	417.6 K	Reid et al. (1987)
Vapor pressure constants		
a	$1.93577\text{x}10^{5}$	Reid et al. (1987)
b	-6112.03	Reid et al. (1987)
c	-352.64	Reid et al. (1987)
Ideal gas heat capacity constants		
a	$-3.571\text{x}10^{-2}$	Reid et al. (1987)
b	$7.4633\text{x}10^{-4}$	Reid et al. (1987)
c	$-2.3946\text{x}10^{-7}$	Reid et al. (1987)
d	$2.90848\text{x}10^{-11}$	Reid et al. (1987)
Reference liquid density	880 gm/cm^3	Reid et al. (1987)
Liquid viscosity constants		
a	0.157647 cp	Reid et al. (1987)
b	924.37 F	Reid et al. (1987)
vaporization enthalpy	182 Btu/lbm-F	Reid et al. (1987)

Table 4.3: Steam recovery pilot well cycling timeline

Time (days)	Event
0.5	Open producer
1.67	Open injectors
3.33	Shut in producer
3.54	Open Producer
3.75	Turn off jackpump
4.79	Turn on jackpump
5.83	Shut in all wells
10.75	Open producer
10.83	Shut in producer
14.33	Open producer
15.33	Open all wells, injectors at 23.5 lbm/hr/well
15.37	Shut in producer
18.33	Open producer
18.46	Shut in all
21.33	Open all wells
21.44	Shut in producer
27.33	Open producer
27.42	Shut in all wells
29.33	Open all wells; injectors at 20 lbm/hr/well
30.08	Pilot study terminated

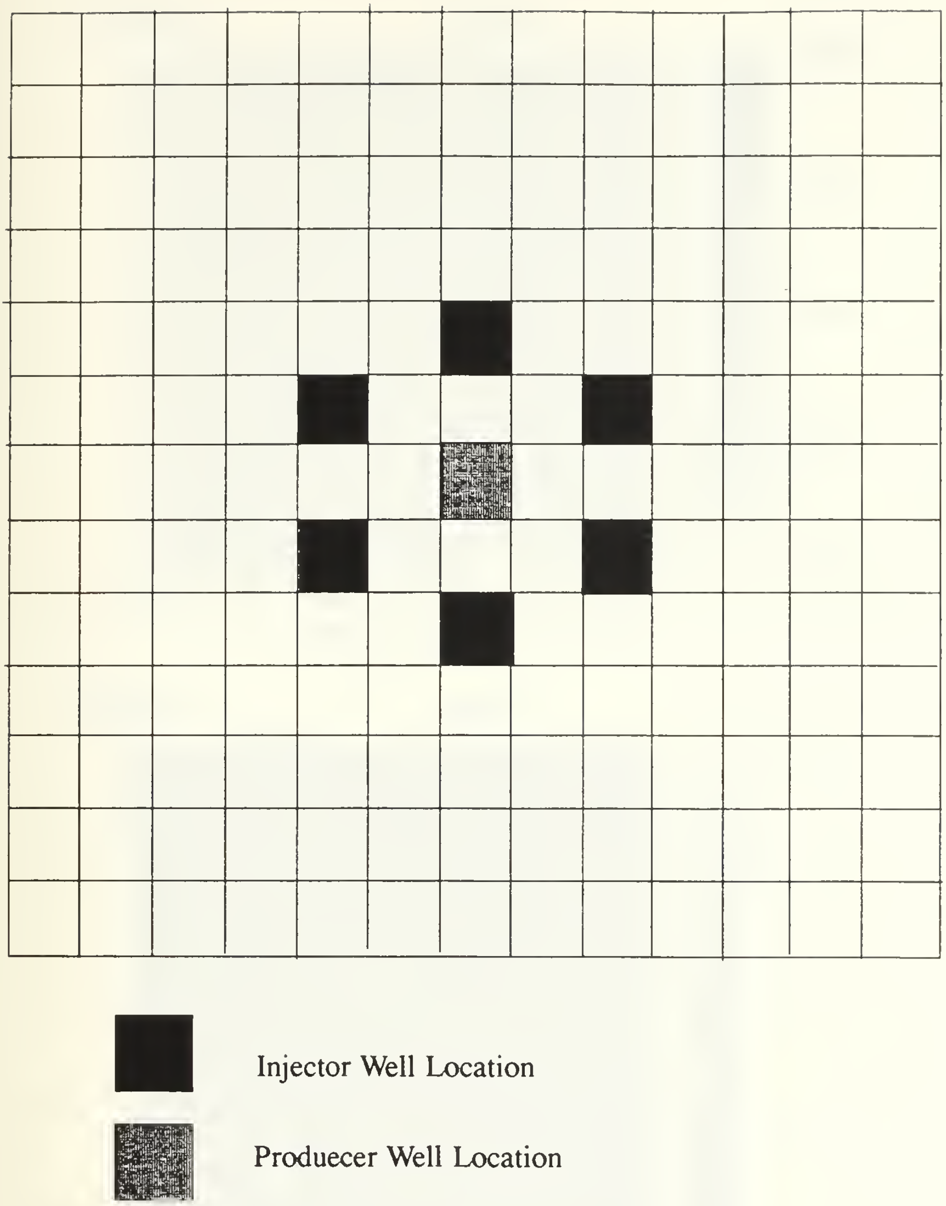

Figure 4.19: Steam pilot well placement

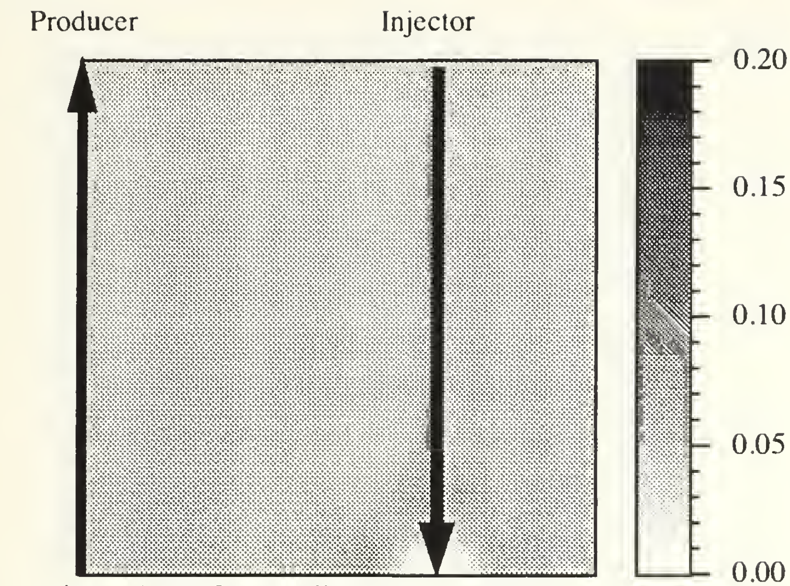

Figure 4.20: Steam pilot 2-D vertical study, saturation profile, t= 2 days

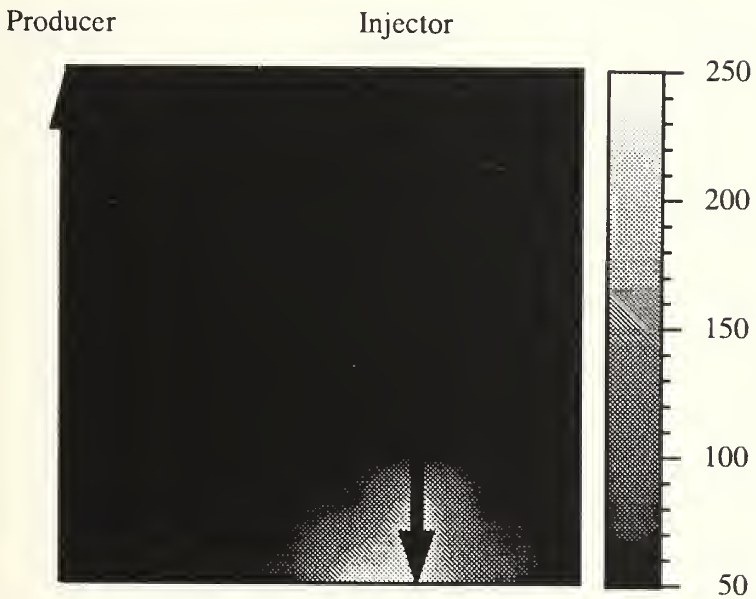

Figure 4.21: Steam pilot 2-D vertical study, temperature profile, t= 2 days

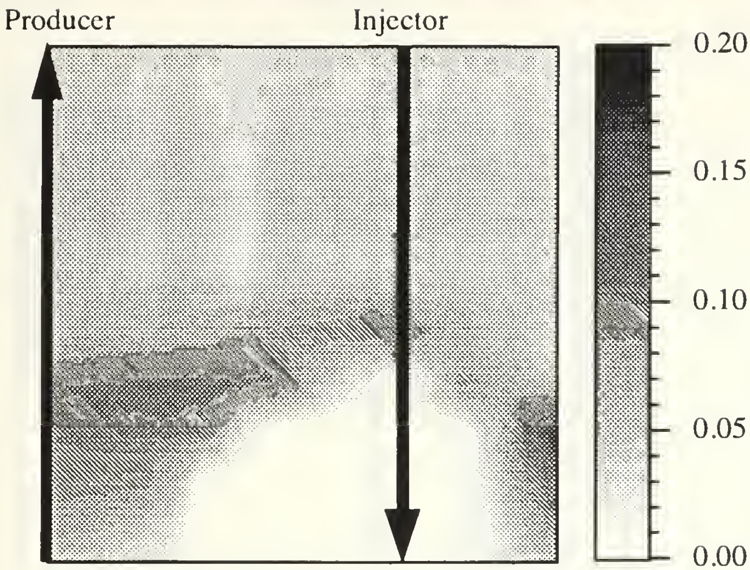

Figure 4.22: Steam pilot 2-D vertical study, saturation profile, t= 3 days

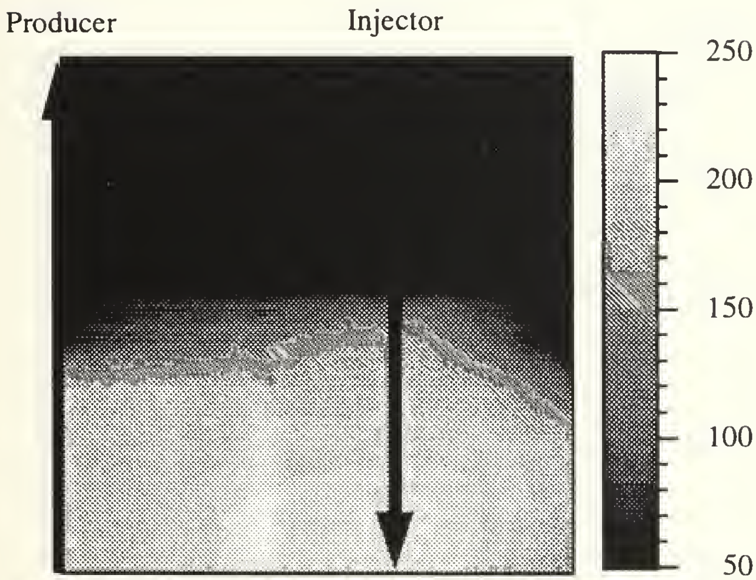

Figure 4.23: Steam pilot 2-D vertical study, temperature profile, t= 3 days

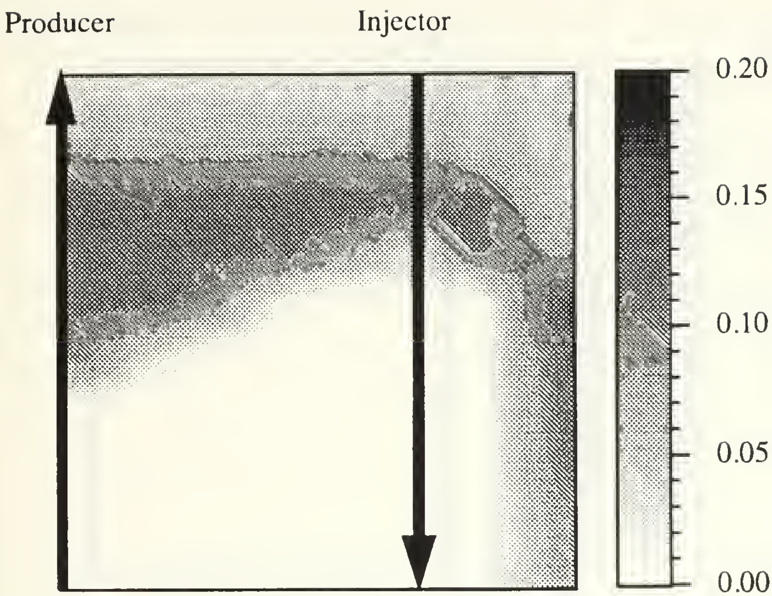

Figure 4.24: Steam pilot 2-D vertical study, saturation profile, t= 5 days

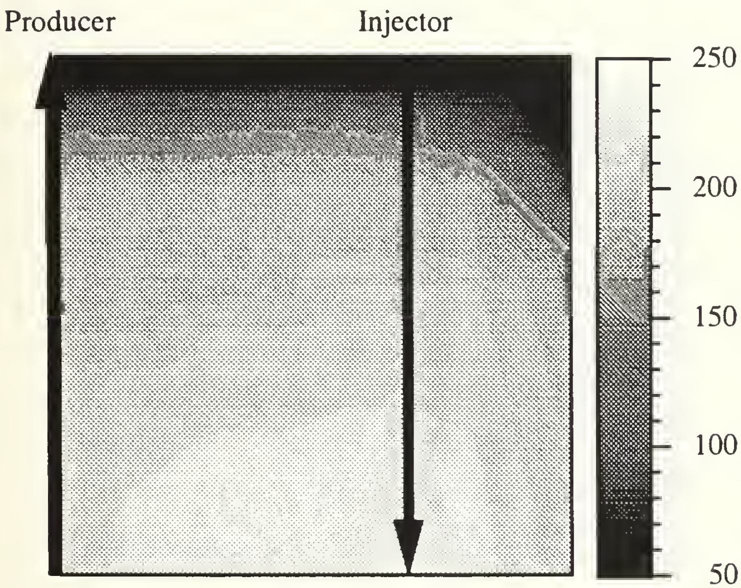

Figure 4.25: Steam pilot 2-D vertical study, temperature profile, t= 5 days

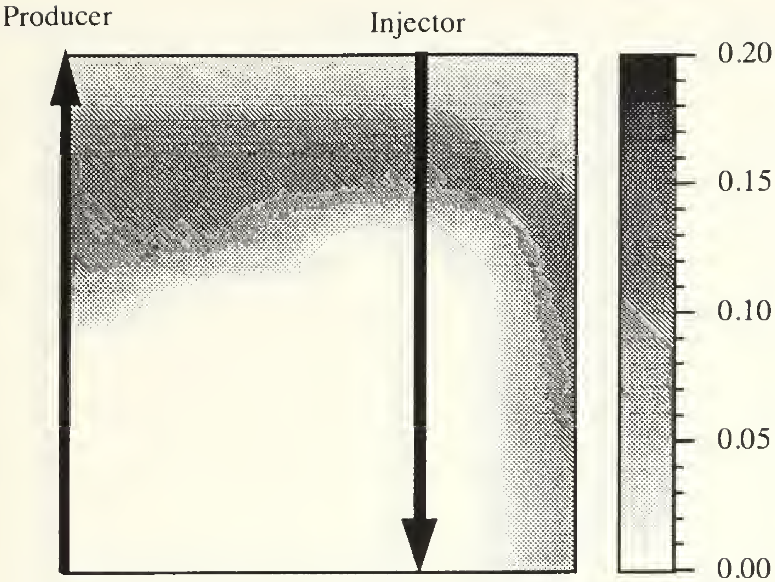

Figure 4.26: Steam pilot 2-D vertical study, saturation profile, t= 10 days

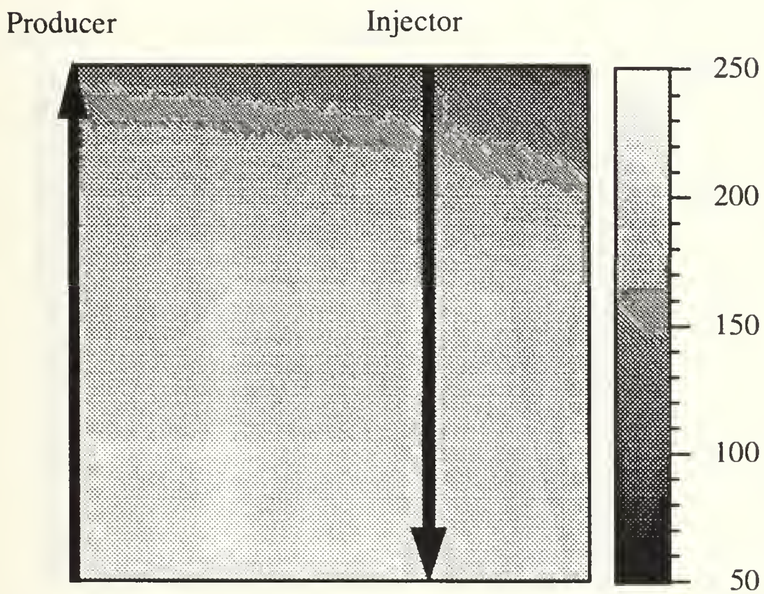

Figure 4.27: Steam pilot 2-D vertical study, temperature profile, t= 10 days

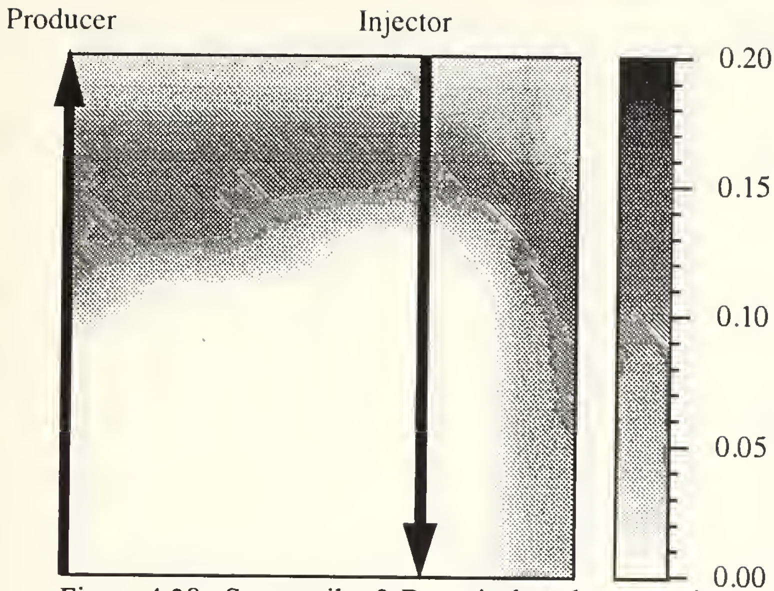

Figure 4.28: Steam pilot 2-D vertical study, saturation profile, t= 15 days

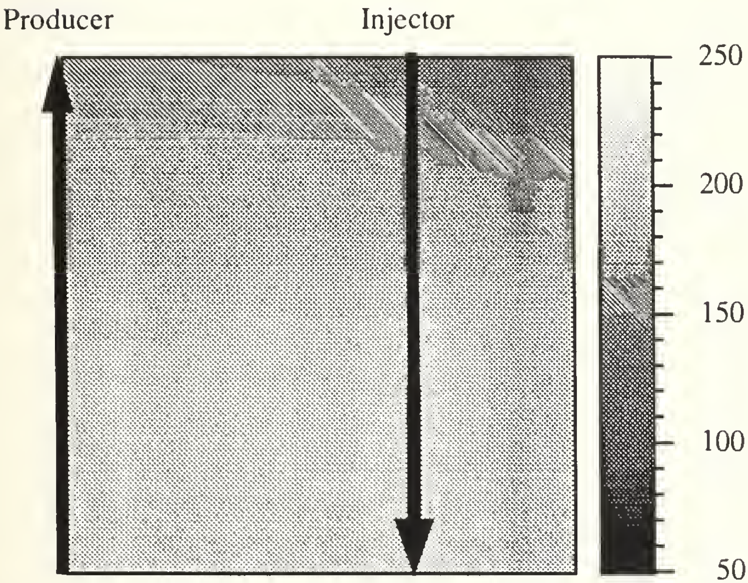

Figure 4.29: Steam pilot 2-D vertical study, temperature profile, t= 15 days

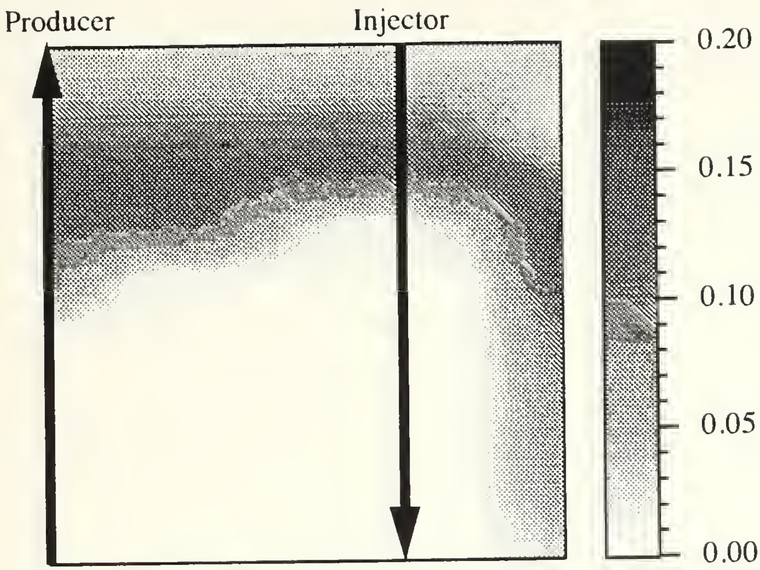

Figure 4.30: Steam pilot 2-D vertical study, saturation profile, t= 21 days

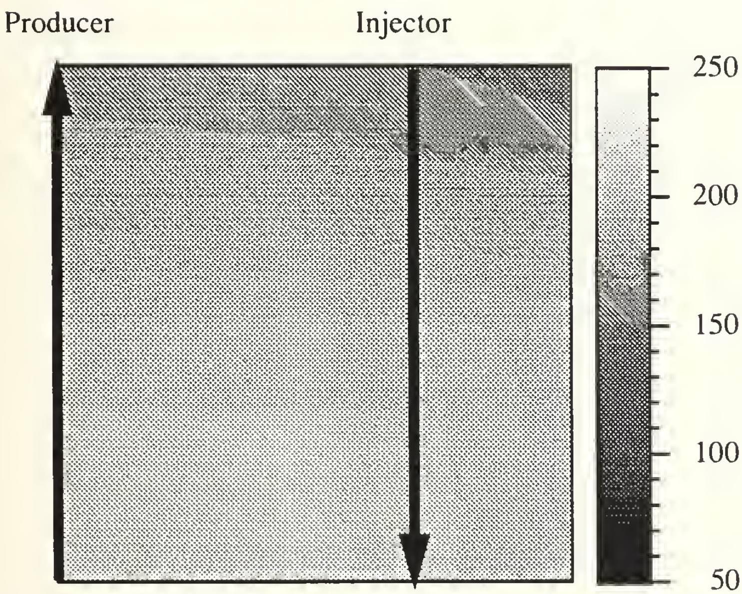

Figure 4.31: Steam pilot 2-D vertical study, temperature profile, t= 21 days

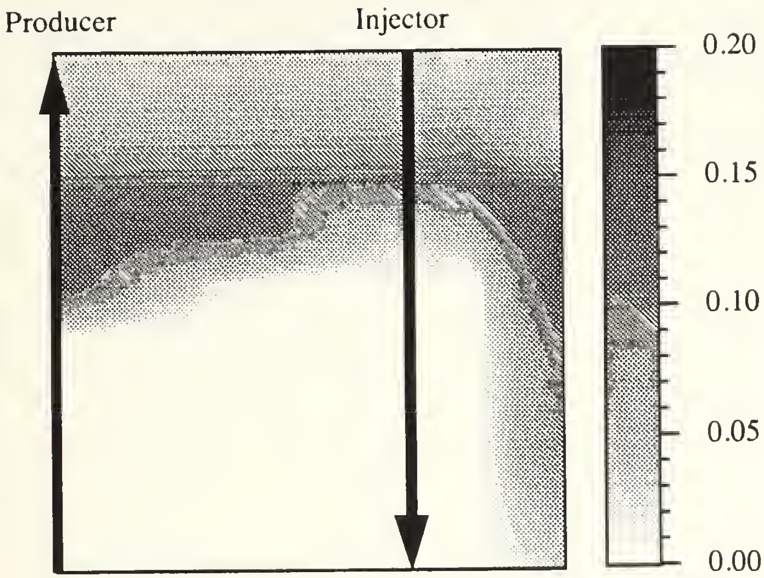

Figure 4.32: Steam pilot 2-D vertical study, saturation profile, t= 25 days

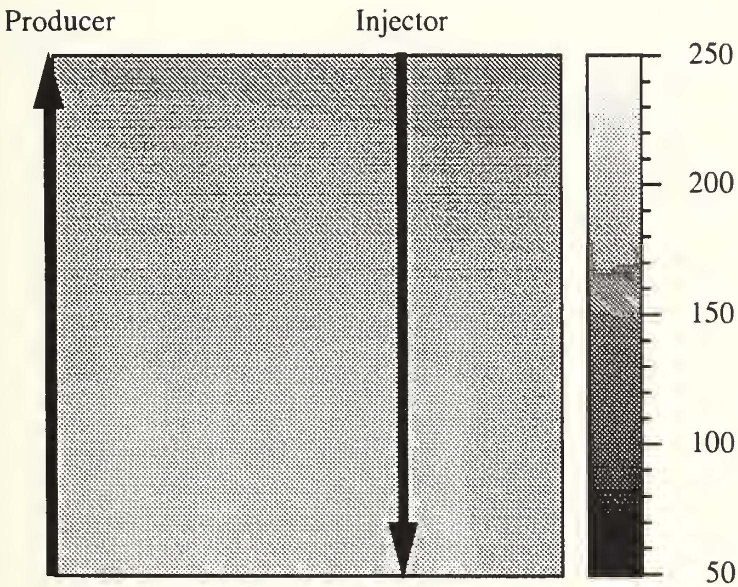

Figure 4.33: Steam pilot 2-D vertical study, temperature profile, t= 25 days

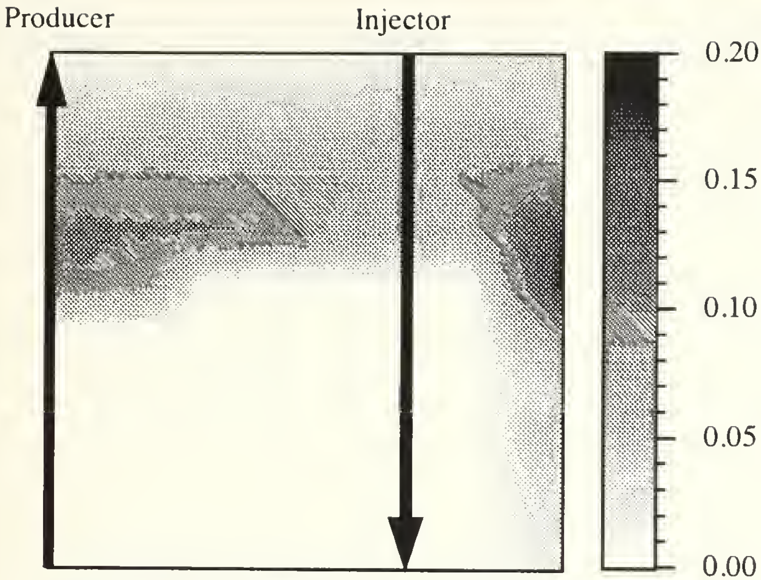

Figure 4.34: Steam pilot 2-D vertical study, saturation profile, t= 33 days

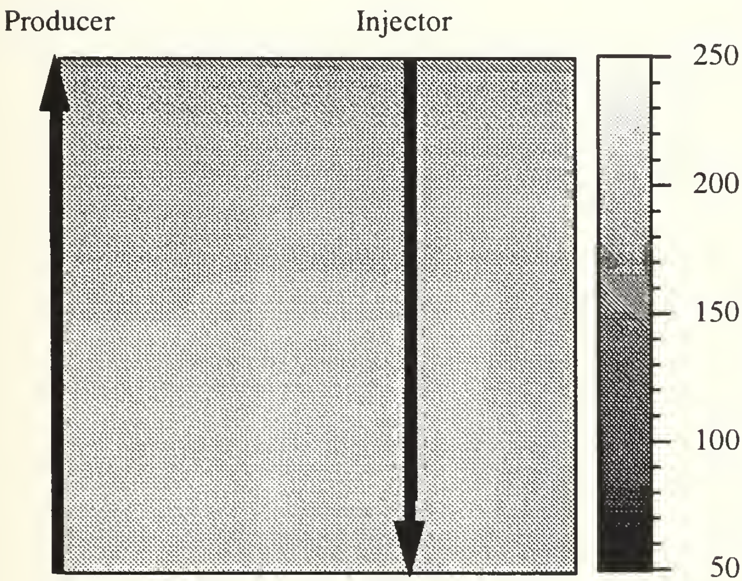

Figure 4.35: Steam pilot 2-D vertical study, temperature profile, t= 33 days

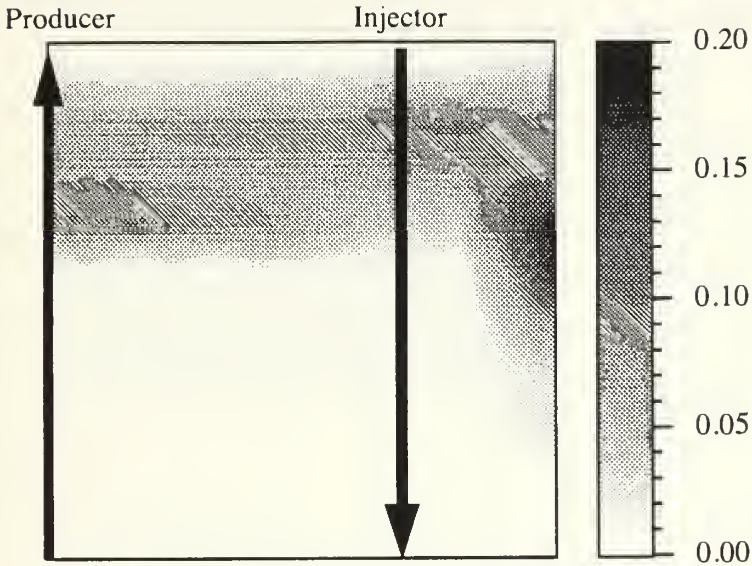

Figure 4.36: Steam pilot 2-D vertical study, saturation profile, t= 40 days

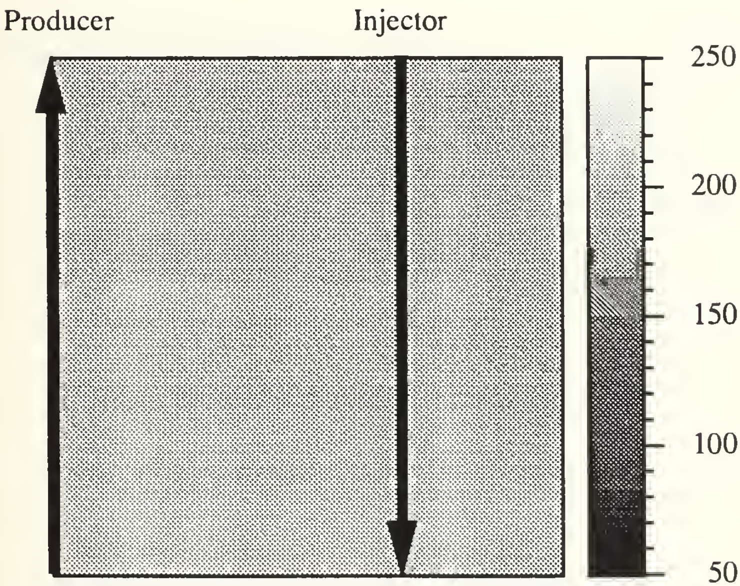

Figure 4.37: Steam pilot 2-D vertical study, temperature profile, t= 40 days

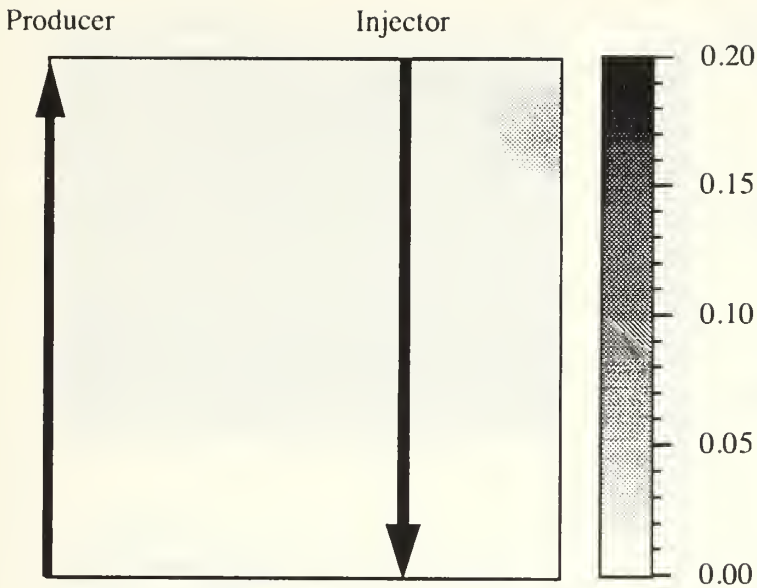

Figure 4.38: Steam pilot 2-D vertical study, saturation profile, t= 60 days

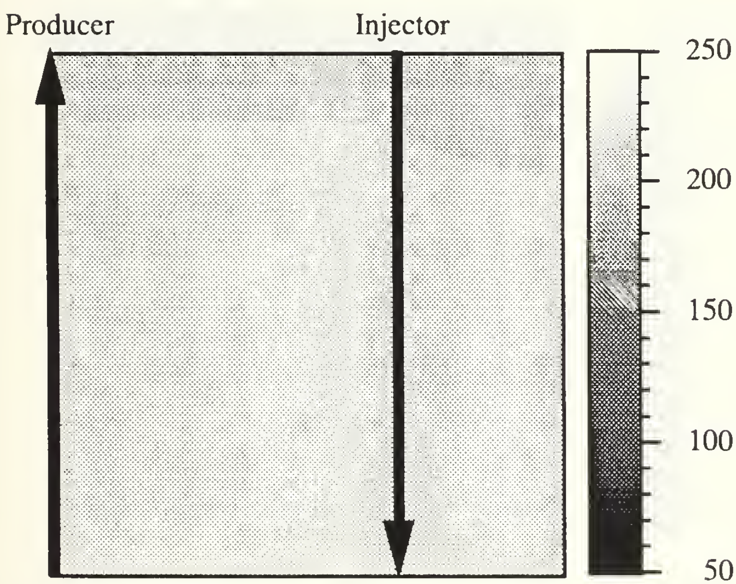

Figure 4.39: Steam pilot 2-D vertical study, temperature profile, t= 60 days

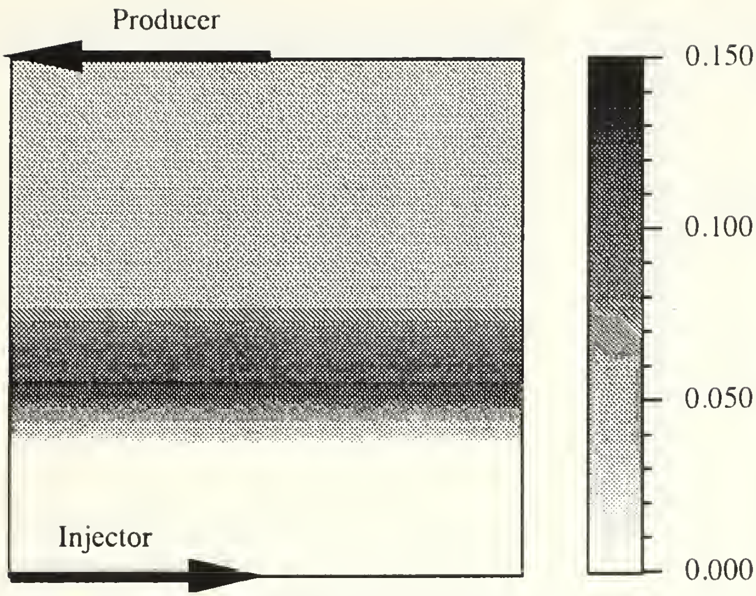

Figure 4.40: Steam pilot 2-D horizontal study, saturation profile, t= 2 days

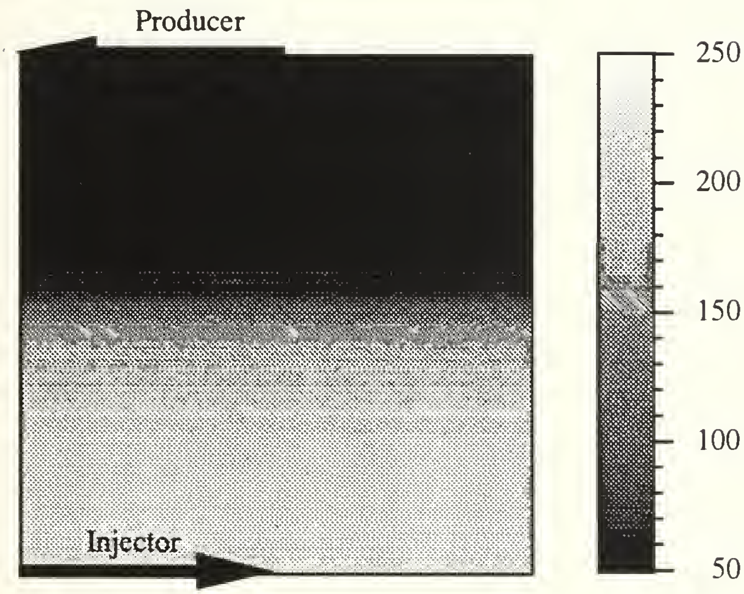

Figure 4.41: Steam pilot 2-D horizontal study, temperature profile, t= 2 days

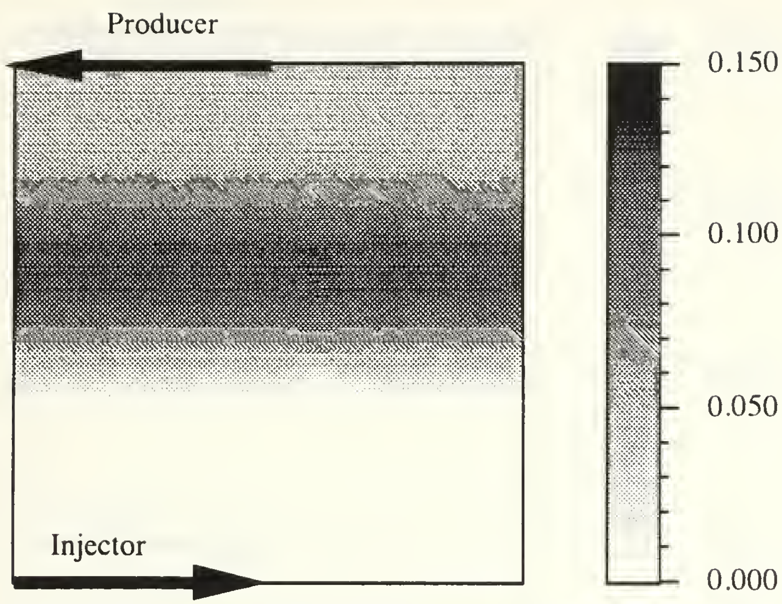

Figure 4.42: Steam pilot 2-D horizontal study, saturation profile, t= 3 days

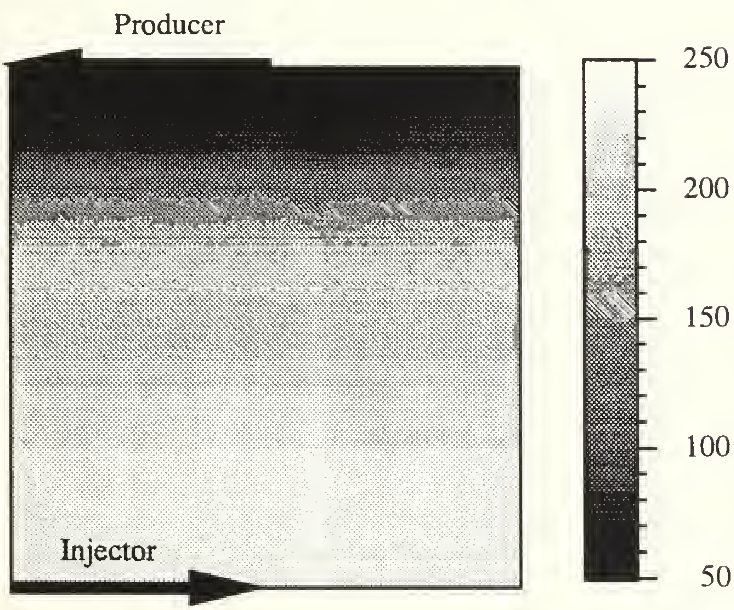

Figure 4.43: Steam pilot 2-D horizontal study, temperature profile, t= 3 days

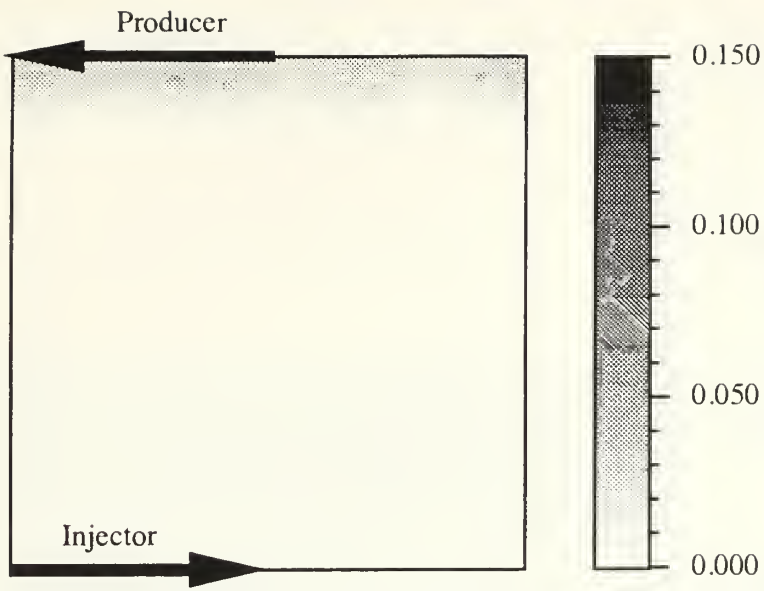

Figure 4.44: Steam pilot 2-D horizontal study, saturation profile, t= 5 days

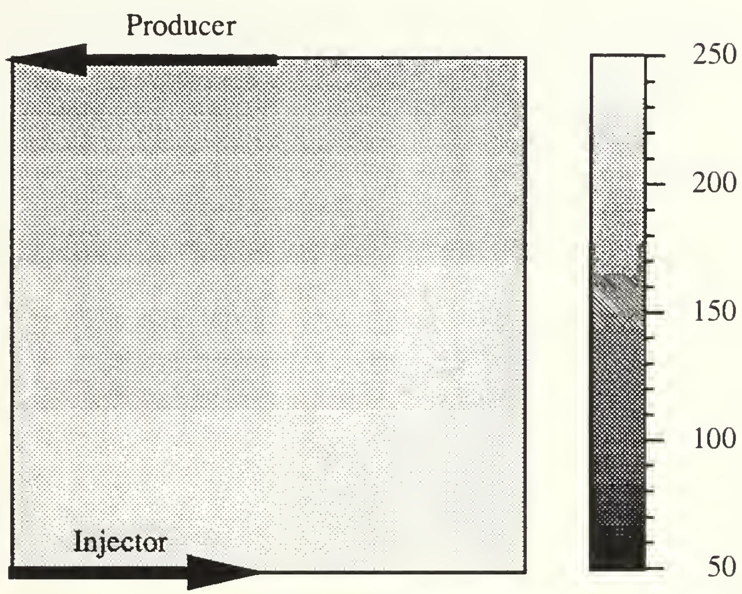

Figure 4.45: Steam pilot 2-D horizontal study, temperature profile, t= 5 days

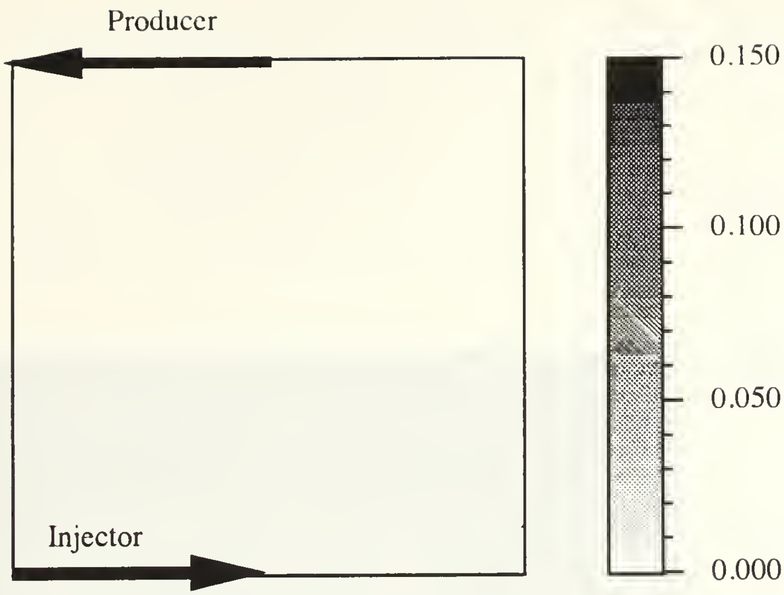

Figure 4.46: Steam pilot 2-D horizontal study, saturation profile, t= 5.2 days

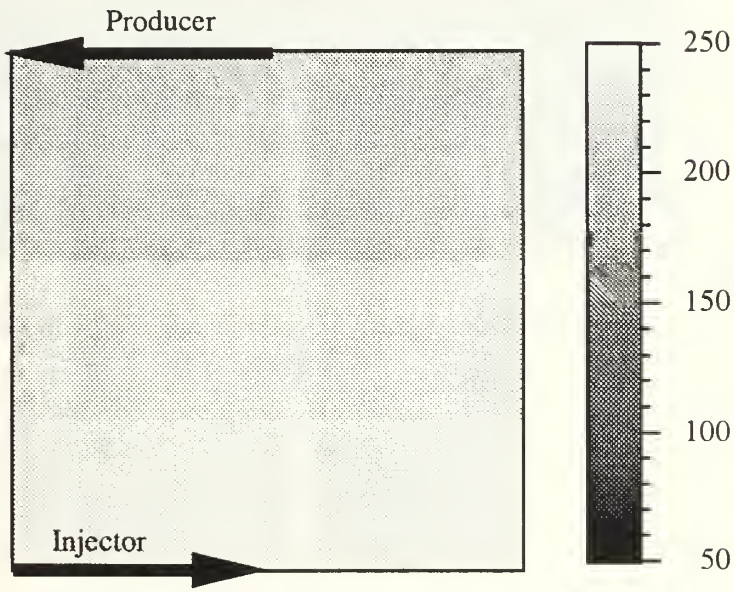

Figure 4.47: Steam pilot 2-D horizontal study, temperature profile, t= 5.2 days

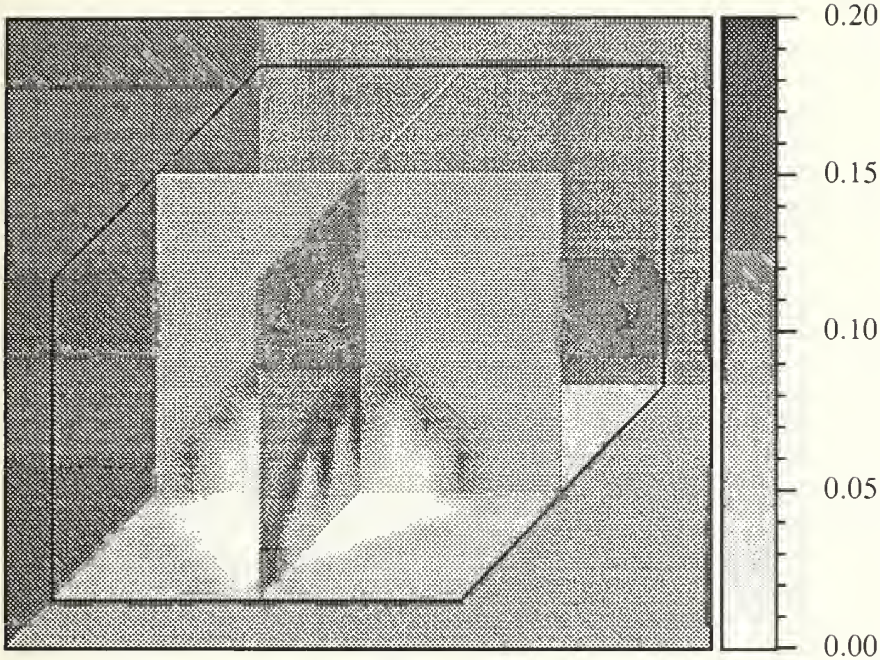

Figure 4.48: Steam pilot 3-D study, saturation profile, t= 2.5 days

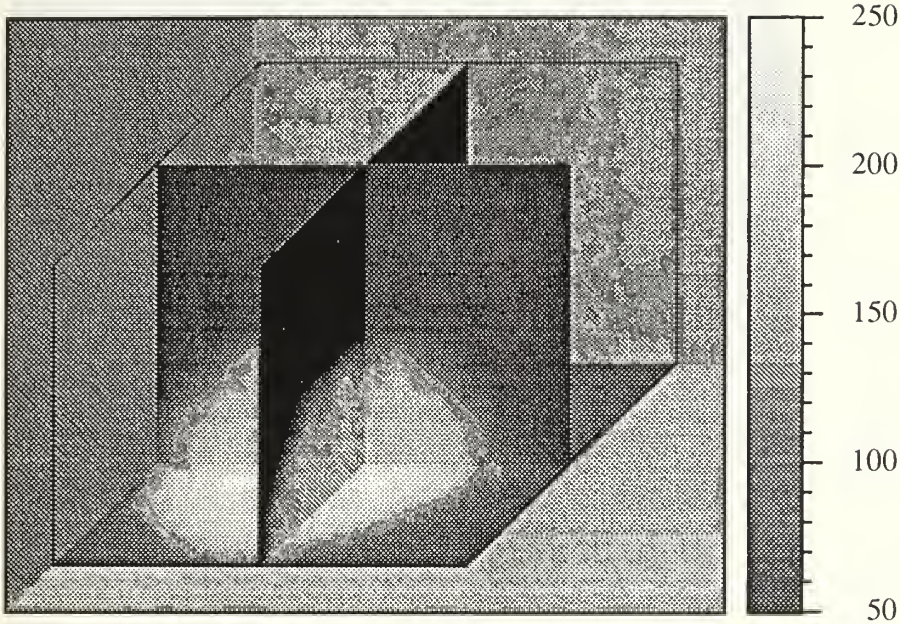

Figure 4.49: Steam pilot 3-D study, temperature
profile, t= 2.5 days

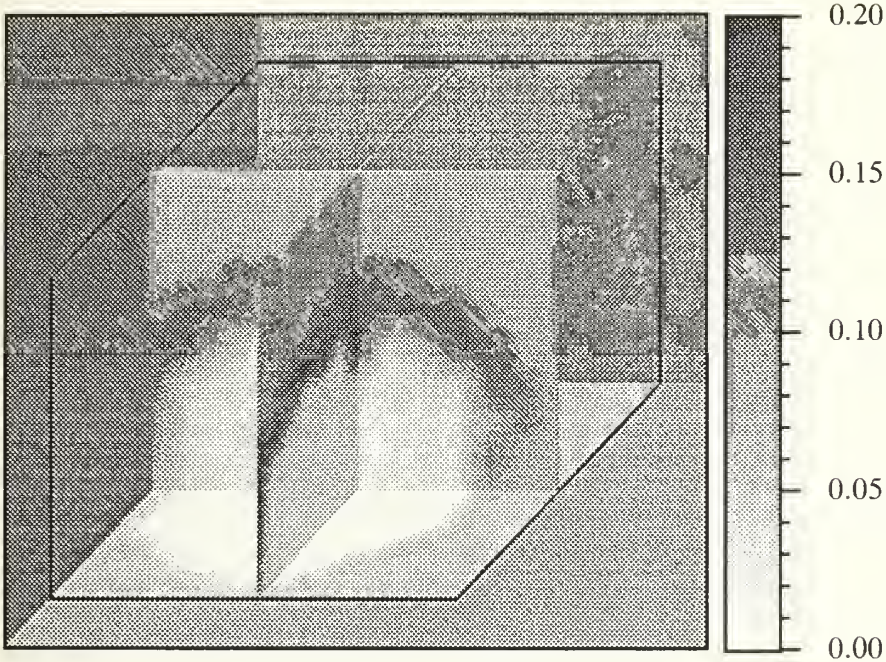

Figure 4.50: Steam pilot 3-D study, saturation profile,
t= 4.5 days

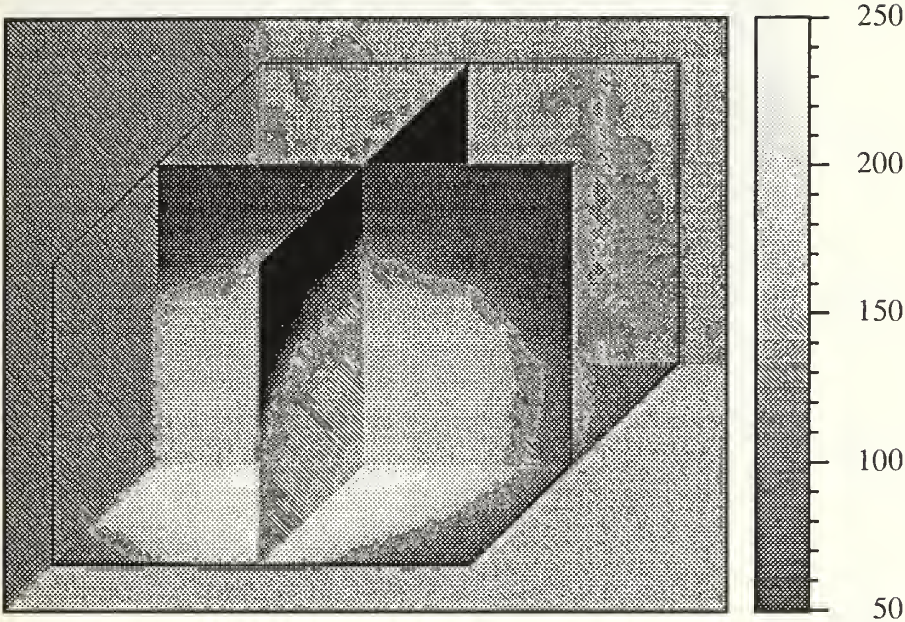

Figure 4.51: Steam pilot 3-D study, temperature
profile, t= 4.5 days

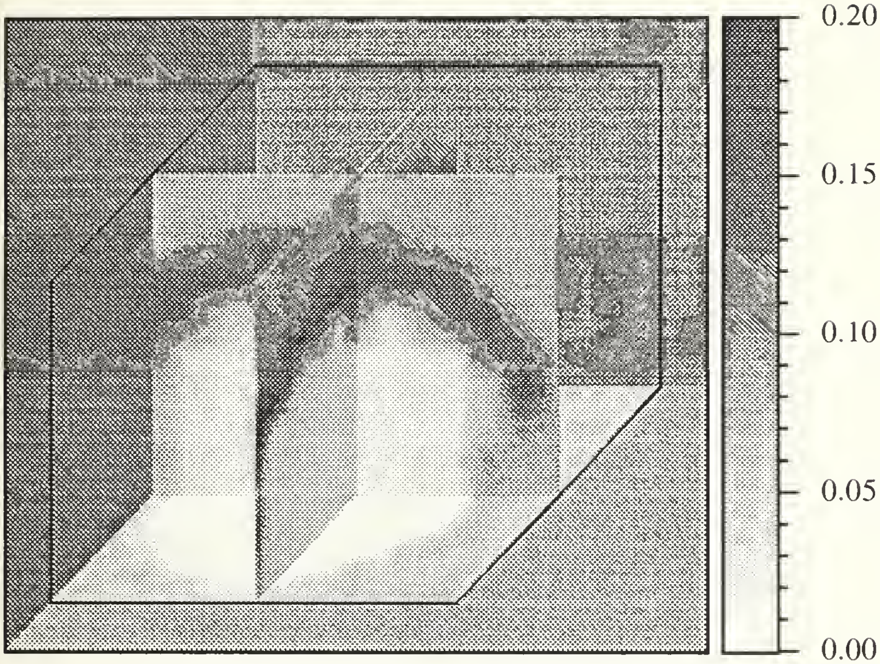

Figure 4.52: Steam pilot 3-D study, saturation profile,
t= 7.5 days

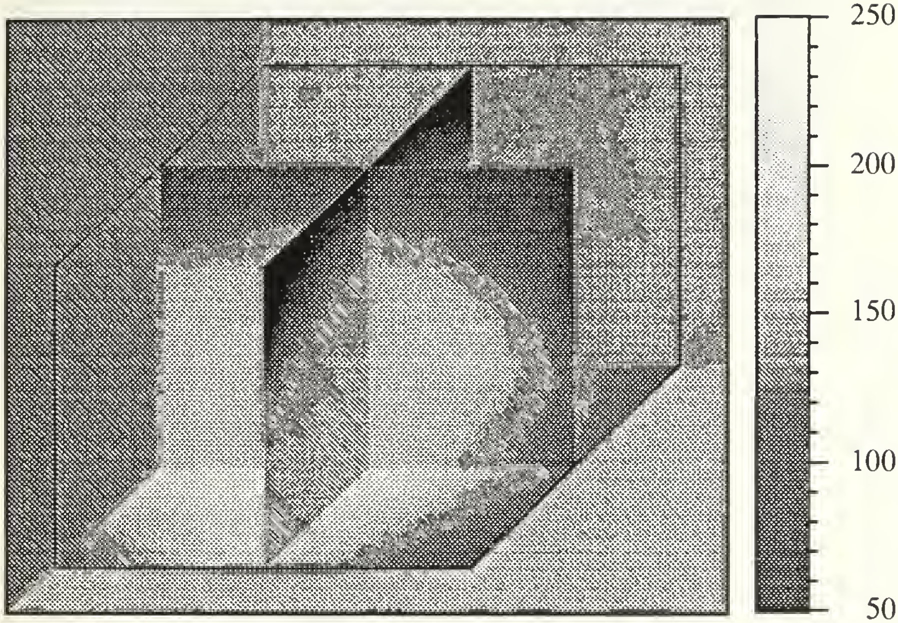

Figure 4.53: Steam pilot 3-D study, temperature profile, t= 7.5 days

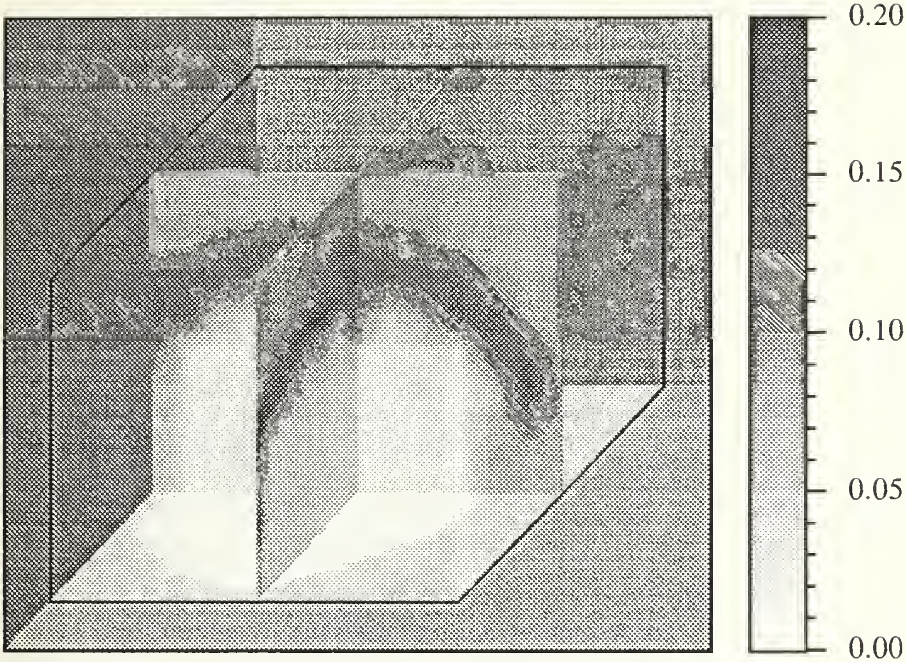

Figure 4.54: Steam pilot 3-D study, saturation profile,
t= 11.3 days

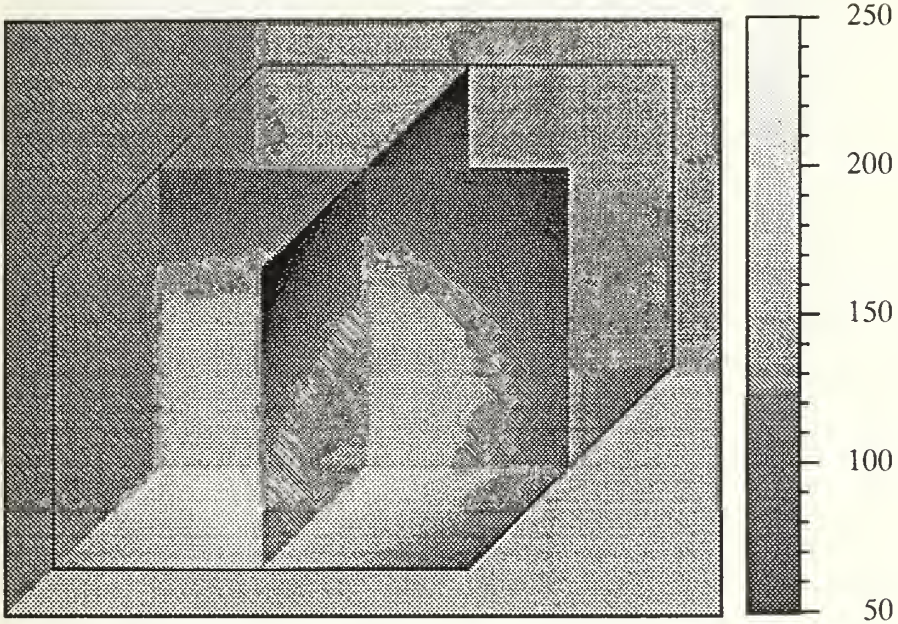

Figure 4.55: Steam pilot 3-D study, temperature profile, t= 11.3days

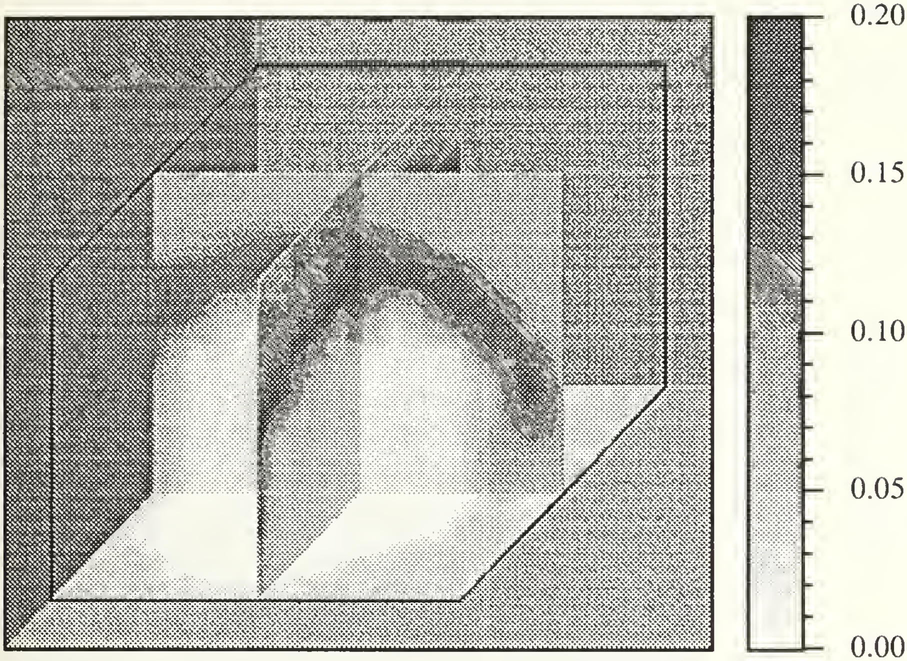

Figure 4.56: Steam pilot 3-D study, saturation profile,
t= 14.3 days

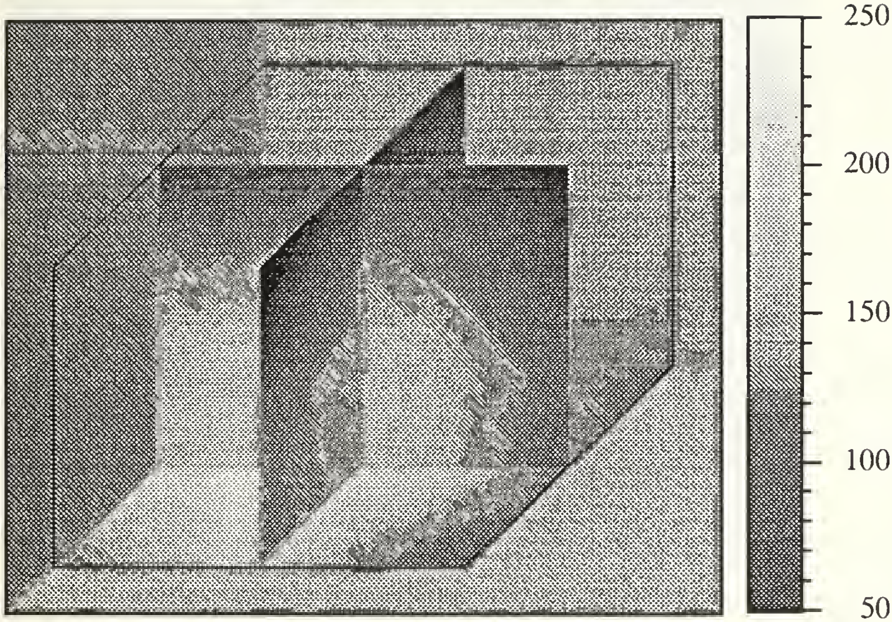

Figure 4.57: Steam pilot 3-D study, temperature profile, t= 14.3days

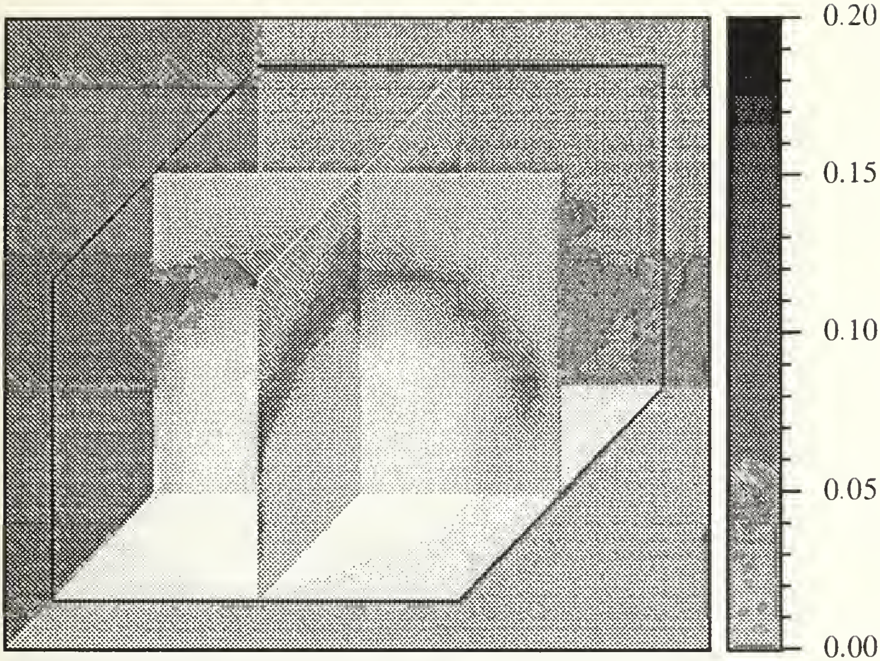

Figure 4.58: Steam pilot 3-D study, saturation profile,
t= 21 days

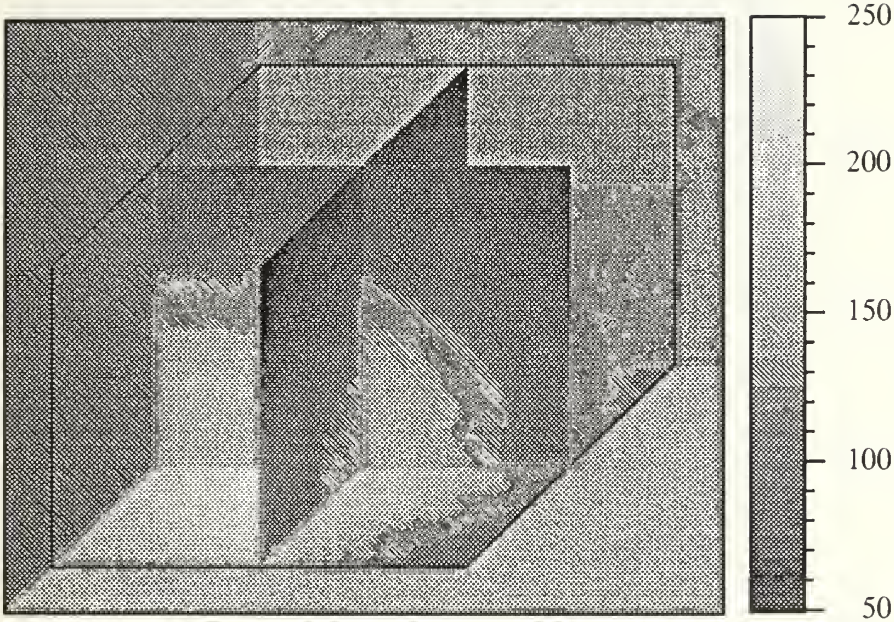

Figure 4.59: Steam pilot 3-D study, temperature
profile, t= 21 days

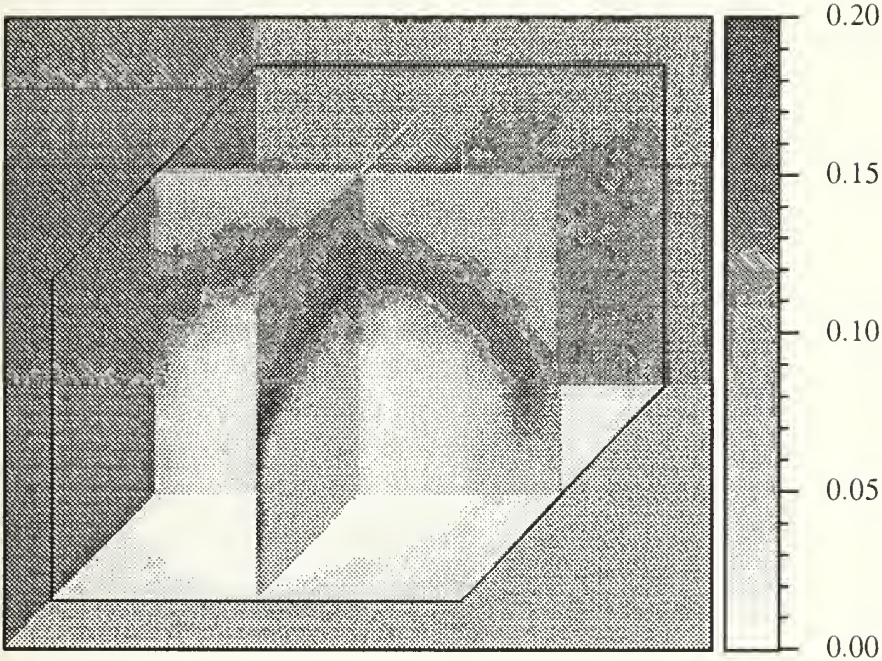

Figure 4.60: Steam pilot 3-D study, saturation profile,
t= 25 days

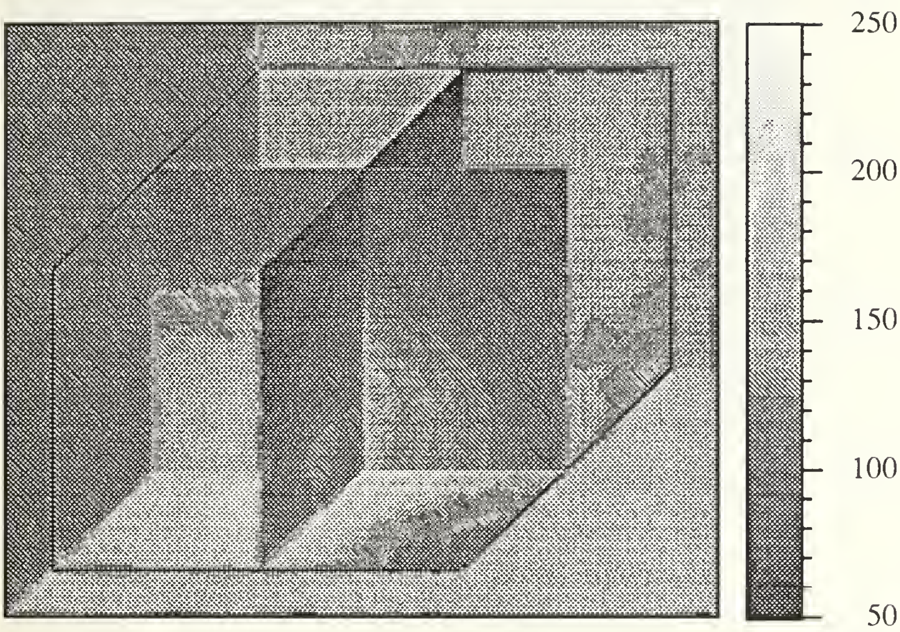

Figure 4.61: Steam pilot 3-D study, temperature profile, t= 25 days

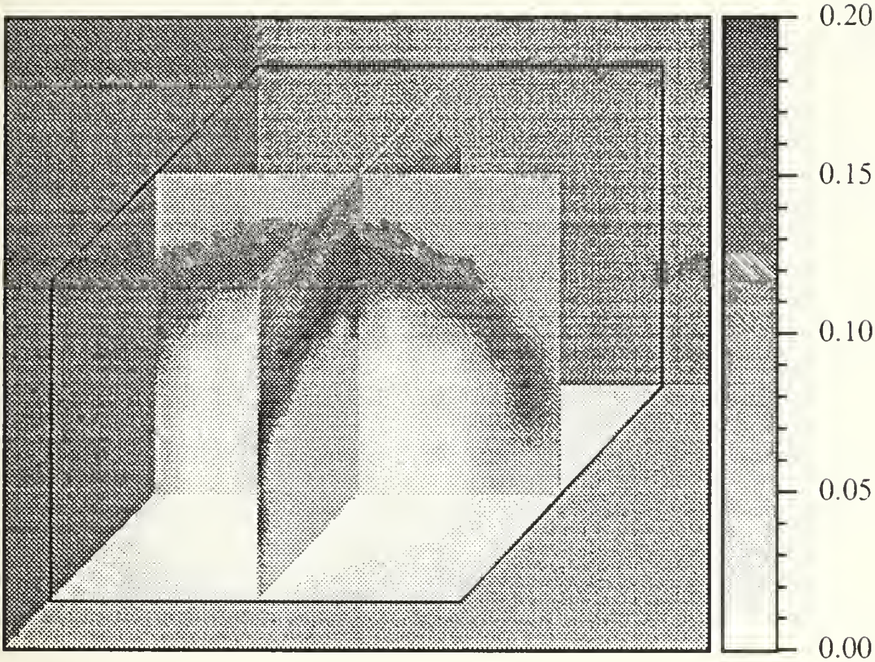

Figure 4.62: Steam pilot 3-D study, saturation profile,
t= 30 days

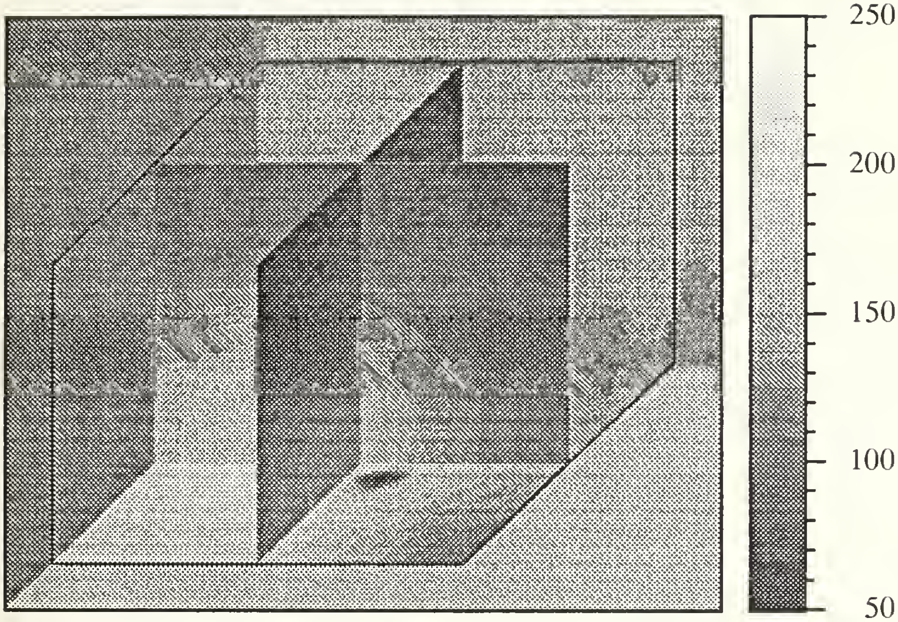

Figure 4.63: Steam pilot 3-D study, temperature profile, t= 30 days

5. CONCLUSIONS AND RECOMMENDATIONS

Based on the results from the simulation studies of steamflood remediation of a contaminated unsaturated zone, the following conclusions and recommendations are made.

CONCLUSIONS

1. The STARS simulator can be used to model steam injection remediation of contaminants in the shallow unsaturated zone.
2. Care must be taken to obtain complete and accurate physical data relating to the contaminants and the contaminated region.
3. Horizontal injection and recovery wells dramatically improve the recovery process.

RECOMMENDATIONS

1. Additional field tests are needed to obtain a good understanding of the peculiarities of working at shallow depths with steam, and the inherent dangers involved.
2. Additional simulation also needs to be performed to: a) develop optimization procedures, and b) to analyze different boundary conditions such as an open surface and a water-saturated zone immediately beneath the surface to act as a steam trap.

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This report was typed by the author.